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Note.--Part 2 of this Journal is the 1961-7 Newsletter of the Highway Division.

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Journal of the
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PREFABRICATED REDUCERS AS ENTRANCES FOR PIPE CULVERTS

By Harvey G. Aronson,[1] A.M. ASCE

SYNOPSIS

Preliminary studies indicate that the flow in a reducer entrance will prime naturally. The resultant subatmospheric pressures will become effective discharge energy, sufficiently high to establish flow control at the larger opening, and a reasonable prediction of the improved flow rate can be made.

INTRODUCTION

A special tapered entrance is an accepted method of improving the flow in a pipe culvert. The actual use of these special entrances have been limited because, the mechanics of operation are not completely understood, thus requiring cautious design criteria, and because the economy effected by the reduction in pipe sizes may be more than offset by the cost of constructing the special entrance.

Eccentric pipe reducers are available as a standard prefabricated item. These reducers are furnished in any combination of pipe diameters, with tapers starting at 3 in. per 2 ft, and are available in the types of materials generally used for highway culverts. They can be installed as easily as straight pipe, and can be used in conjunction with standard square-edge headwalls.

Therefore, although these reducers are intended for other purposes by the manufacturers, they lend themselves to use as economical tapered pipe culvert entrances because of their ease of installation and standard sizes and tapered lengths. There is a resultant probability of improved hydraulic operation and the development of reliable design criteria.

Note.—Discussion open until August 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. HW 1, March, 1961.

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The extent of this improved flow condition is explored here to a limited degree. Included are analogous analyses of results from tests on special culvert inlet models, which were conducted by others; results of tests on an eccentric reducer, which were conducted by the author; and finally, the application of test results and their theoretical implications in pipe culvert design.

Notation.—The letter symbols adopted for use in this paper are defined where they first appear, in the illustrations or in the text, and are arranged alphabetically, for convenience of reference, in the Appendix.

REVIEW OF FUNDAMENTAL CONCEPTS

Culverts with submerged inlets will form a contraction or jet at the entrance when the depth of flow in the culvert is less than the depth of the culvert (Fig. 1). Flat slopes or effective tailwater depths will generally submerge the contraction.

If the culvert entrance is primed the contraction will be greatly minimized, the culvert will flow full on flat slopes, and, on steep slopes, it will discharge significantly higher than the culvert with an unprimed entrance.

Several reports[2,3,4] demonstrate inlet entrances for box culverts and pipe culverts that prime naturally and flow full. However, design engineers using these model shapes for their full scale designs generally limit the design improvement to a decrease in the entrance coefficient.

If this generally accepted procedure is applied to a culvert with a submerged reducer entrance, the energy equations for both the primed and the non-primed operation would be similar, if entrance losses are discounted. They would be placed in three general classifications as follows:

1. The flat slope discharge (Fig. 2(a)) will be controlled by the outlet at point 3. The energy equation is

$$H_h = D_1 + \frac{V_1^2}{2\,g} + \frac{p_1}{w} = D_2 + \frac{V_2^2}{2\,g} + \frac{p_2}{w} = D_3 + \frac{V_3^2}{2\,g} + h_e - S\,L \quad \ldots \quad (1)$$

$(S\,L < h_e)$ in which

$$h_e = f\,\frac{L}{R}\,\frac{V^2_{mean}}{2\,g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2a)$$

and

$$f = \frac{2\,g\,n^2}{R^{1/3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2b)$$

2 "Model Studies of Tapered Inlets for Box Culverts," by R. H. Shoemaker and L. A. Clayton, Highway Research Bd. Research Report 15-B, 1953.

3 "Model Studies of Inlet Designs for Pipe Culverts on Steep Grades," by M. H. Karr and L. A. Clayton, Bulletin No. 35, Engrg. Experiment Sta., Oregon State College, June, 1954.

4 "Hydraulics of Closed Conduit Spillways, Part X the Hood Inlet," by F. W. Blaisdell and C. A. Donnelly, St. Anthony Falls Lab., Univ. of Minnesota, Tech. Paper No. 20, Series B, 1958.

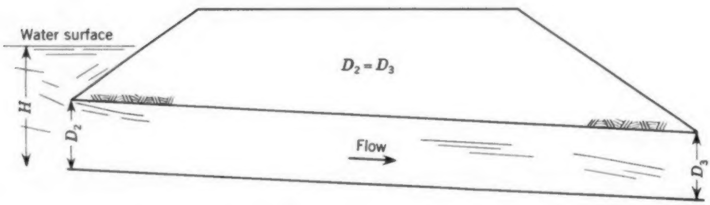

FIG. 1.—CULVERT WITH SUBMERGED INLET

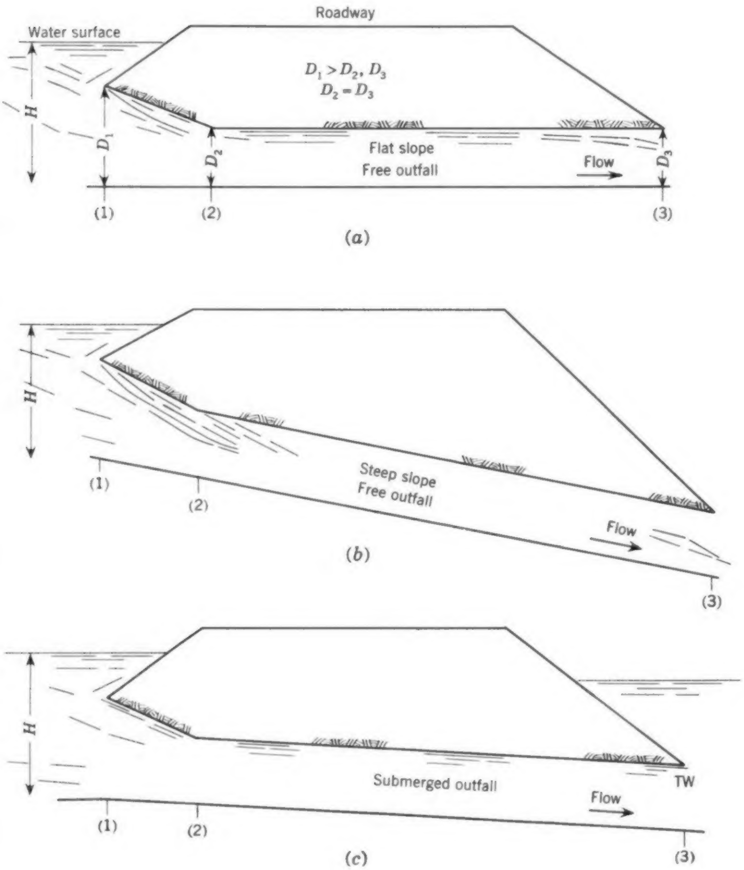

FIG. 2.—VARYING DISCHARGE CONFIGURATIONS

2. When the slope of the pipe is sufficiently steep (Fig. 2(b)), discharge control is at point 2, and the energy equation is

$$H = D_1 + \frac{{V_1}^2}{2\ g} + \frac{p_1}{w} = D_2 + \frac{{V_2}^2}{2\ g} \quad \text{. . . . . (3)}$$

$(S\ L \geqq h_e)$

3. When the outfall is submerged (Fig. 2(c)), the discharge is governed by the outlet at point 3, and the energy equation is

$$H = H_t + \frac{{V_1}^2}{2\ g} + \frac{p_1}{w} = H_t + \frac{{V_2}^2}{2\ g} + \frac{p_2}{w} = H_t + \frac{{V_3}^2}{2\ g} + h_e - S\ L \quad \text{. . . (4a)}$$

$$\left(H_t > D_1 + S\ L\right)$$

or

$$H = D_1 + \frac{{V_1}^2}{2\ g} + \frac{p_1}{w} + H_t + \frac{{V_2}^2}{2\ g} + \frac{p_2}{w} + H_t + \frac{{V_3}^2}{2\ g} + h_e - S\ L \quad \text{. . . (4b)}$$

$$\left(H_t < D + S\ L > S\ L\right)$$

In the preceding equations H_h refers to the headwater elevation or depth above the inside bottom of the pipe at the entrance, in feet; D denotes the depth of flow in the pipe, in feet; V is the mean velocity, in feet per second; p/w refers to the static pressure head, in feet; g is the acceleration due to gravity; h_e denotes the loss of head through the pipe culvert; S refers to the slope of the pipe culvert; L is the effective length of the pipe culvert; f denotes the friction factor; n is the Manning roughness coefficient; R refers to the hydraulic radius; and H_t denotes the tailwater elevation or depth above the inside bottom of the pipe at the outlet, in feet.

NEW CONCEPT THEORY

If the reducer primes naturally, and the resultant subatmospheric pressures become effective discharge energy, the flow will be controlled at the entrance (point 1 in Fig. 2), and will be based on the larger opening at point 1 and the headwater depth at this opening.

The energy equations for priming reducer operation would be different from Eqs. 1, 3 and 4.

Flat slope pipe:

$$H_h = D_1 + \frac{{V_1}^2}{2\ g} \quad \text{. . . . . (5)}$$

and

$$E = D_1 + \frac{{V_1}^2}{2\ g} + p_{a_{sub}} \quad \text{. . . . . (6a)}$$

$\left(H_h < D_2 + \frac{{V_2}^2}{2\ g}\right)$. At point 2

$$E = D_2 + \frac{V_2^{\,2}}{2\,g} + p_{a_{sub}} \quad \ldots\ldots\ldots\ldots\ldots \quad (6b)$$

with

$$p_{ae_{sub}} \geq h_e - S\,L \quad \ldots\ldots\ldots\ldots\ldots \quad (7a)$$

and

$$p_{a_{sub}} \geq D_2 + \frac{V_2^{\,2}}{2\,g} - \left(D_1 + \frac{V_1^{\,2}}{2\,g}\right) + p_{ae_{sub}} \quad \ldots \quad (7b)$$

Steep slope pipe:

$$H_h = D_1 + \frac{V_1^{\,2}}{2\,g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

and

$$E = D_1 + \frac{V_1^{\,2}}{2\,g} + p_{a_{sub}} \quad \ldots\ldots\ldots\ldots \quad (9a)$$

$\left(H < D_2 + \frac{V_2^{\,2}}{2\,g}\right)$. At point 2

$$E = D_2 + \frac{V_2^{\,2}}{2\,g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9b)$$

with

$$p_{a_{sub}} \geq D_2 + \frac{V_2^{\,2}}{2\,g} - \left(D_1 + \frac{V_1^{\,2}}{2\,g}\right) \quad \ldots\ldots\ldots \quad (10)$$

$$H_h = D_1 + \frac{V_1^{\,2}}{2\,g} \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

Submerged outfall:

$$E = D_1 + \frac{V_1^{\,2}}{2\,g} + p_{a_{sub}} \quad \ldots\ldots\ldots\ldots \quad (12a)$$

At point 2

$$E = D_2 + \frac{V_2^{\,2}}{2\,g} + p_{ae_{sub}} \quad \ldots\ldots\ldots\ldots \quad (12b)$$

with

$$H < D_2 + \frac{V_2^{\,2}}{2\,g} \quad \ldots\ldots\ldots\ldots\ldots \quad (13)$$

$$p_{ae_{sub}} \geq H_t - D_2 + h_e - S\,L \quad \ldots\ldots\ldots\ldots \quad (14)$$

and

$$p_{a_{sub}} \geq D_2 + \frac{V_2^{\,2}}{2\,g} - \left(D_1 + \frac{V_1^{\,2}}{2\,g}\right) + p_{ae_{sub}} \quad \ldots\ldots \quad (15)$$

In the preceding equations E is the energy; $p_{a_{sub}}$ is the effective subatmospheric pressure, in feet; and $p_{ae_{sub}}$ residue subatmospheric pressure at the small end of the reducer, the effective subatmospheric pressure.

Therefore, for all conditions in which $p_{ae_{sub}}$ is sufficiently large, there will be the one equation based on the larger opening (point 1), and the headwater depth at this opening:

$$H = D_1 + \frac{V_1^2}{2g} + C_e \quad \ldots\ldots\ldots\ldots \quad (16)$$

in which C_e is the entrance velocity head.

DESCRIPTION OF REDUCER OPERATION

Subatmospheric Air Pressure By Air Channel Block.—Consider a culvert with a reducer entrance and a headwater depth H_h just below the top of the entrance (Fig. 3). Static pressure is not yet required at point 1, and the discharge is governed by the diameter at points 2 or 3. When the headwater

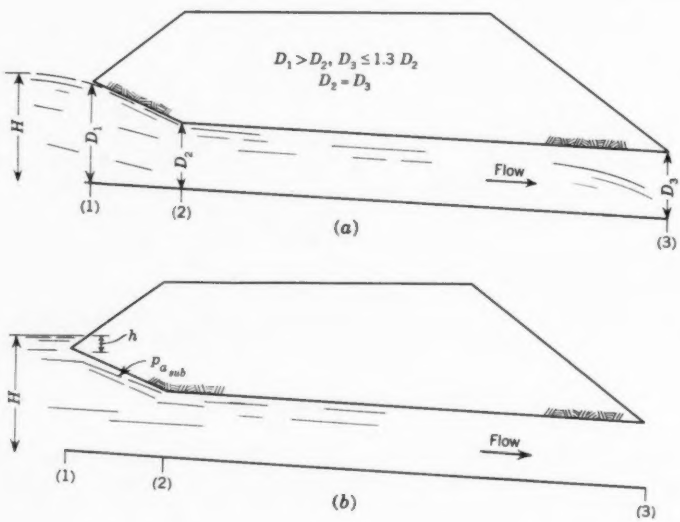

FIG. 3

rises sufficiently to submerge the entrance (for a straight pipe entrance this will occur at 1.2 D_2 - 1.5 D_2, for a reducer entrance less than 1.4 D_2), the velocity entrance losses increase, the momentum of flow in the entrance remains the same initially, and the culvert control reverts to point 1, and an instant lesser discharge. The velocity of flow just inside the entrance is then greater than the velocity of flow entering the reducer. Because the reducer is flowing full near point 2, air cannot enter the entrance of the reducer through the outlet, and the differential flow results in a partial vacuum (Fig. 3(b)). Water flows into this vacuum based on a velocity head equal to h = par-

tial p_a; the voids instantly fill, and the energy of velocity becomes instant static pressure.

$$p_{s_I} = h + p_a \quad \text{(17)}$$

The culvert discharges this orifice flow plus the generally small volume that has been discharged into the void. The velocity of flow at the reducer entrance is less than this discharge velocity. Thus, separation occurs again, and the cycle is repeated. This pattern of flow is stable, and similar for all depths provided that the following conditions exist:

1. The culvert outlet is not submerged during the transition from free to submerged entrance. The culvert will continue to prime naturally if the outlet is submerged after the priming operation has started.
2. The total energy loss through the culvert is equal to, or less than the effective instant static pressure.

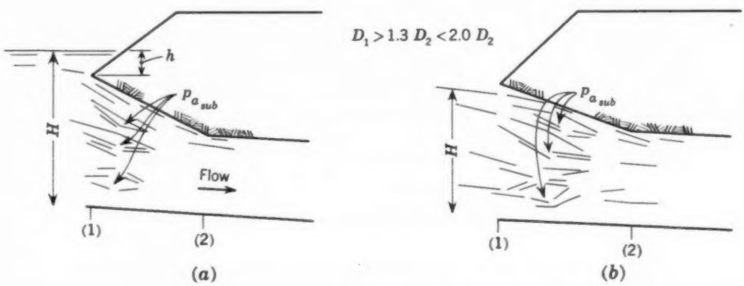

FIG. 4.—SUBATOMSPHERIC PRESSURES BY RAPID VELOCITY CHANGE

Subatmospheric Pressure By Rapid Velocity Change.—Within a range of ratios of reducer entrance areas, exit areas, and lengths (beginning at headwater depths of 1.2 to 1.3 D_2), there are sufficiently rapid changes in velocity, necessary to compensate for the differences in the theoretical depths of flow between the taper ends, such that voids are formed in the reducer (Figs. 4(a) and 4(b)). Natural priming will then occur even though the entrance may not be submerged.

Culvert operation under this type of void development continues in a series of cycles similar to and governed by the same conditions as those governing "subatmospheric by air channel block," except that the discharge control is not necessarily at point 1, but at the point in the reducer at which the separation occurs.

TESTS

The theoretical description of the reducer operation raises the following questions:

1. What are the limiting dimensions of a reducer that will prime naturally?

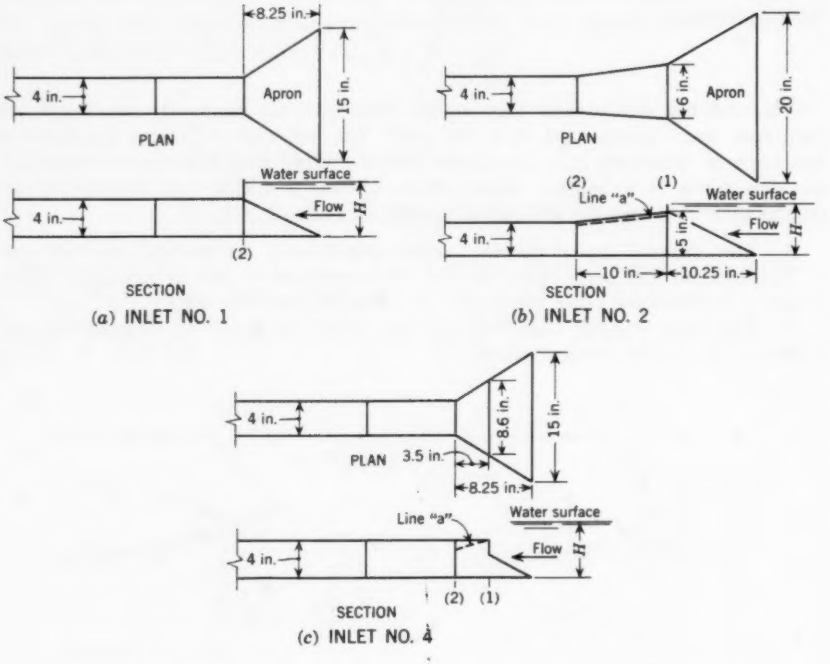

FIG. 5.—INLET MODELS FROM SHOEMAKER AND CLAYTON

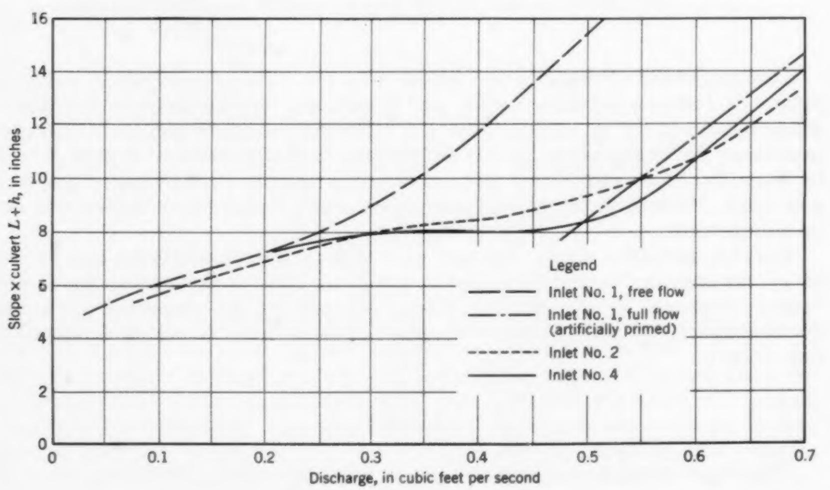

FIG. 6.—DISCHARGE RATING CURVES

2. Is $p_{a_{sub}}$ effective in increasing the pressure in the reducer entrance, and if so, can the extent of this increase in pressure be predicted?

3. Can a reasonably accurate relationship be established between theoretical discharge with control at point 1 and actual discharge with control at point 1, or between theoretical discharge with control at some intermediate point between points 1 and 2 and actual discharge at this intermediate point?

4. What are the range of headwater depths at which priming will occur.

To help provide a solution to these questions, experiments were conducted on a reducer model, and a study was made of applicable portions of several research reports.[2,3,4]

The report of R. H. Shoemaker and L. A. Clayton,[2] F. ASCE, was concerned with model studies of tapered inlets for box culverts. Inlet types 1, 2, and 4 (Fig. 5) are used for this analysis. Table 1(a) and (b) shows some of the

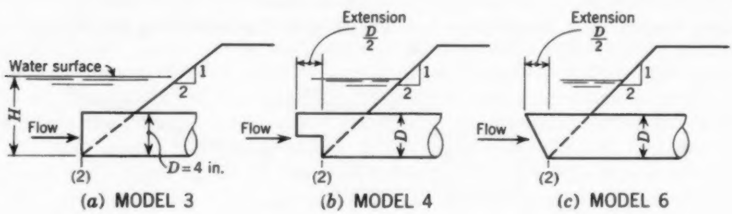

FIG. 7.—INLET MODELS FROM KARR AND CLAYTON

results of this report. Columns 1, 2, 3, and 4 list the discharges, and columns 7 and 8 list the observed headwater depths for these discharges. Fig. 6 duplicates portions of the results graphically.

The report of M. H. Karr and Clayton[3] was concerned with model studies of inlet designs for pipe culverts on steep grades. Models 3, 4, and 6 (Fig. 7) are used for this analysis. Table 2 shows some of the results of this report. Columns 1, 2, 3, and 4 list the discharges, and column 8 lists the observed headwater depths for these discharges.

The report of F. W. Blaisdell and C. A. Donnelly[4] was concerned with model studies of hood inlets for closed conduit spillways. Applicable portions of series 65, 56, and 82 are used for this analysis. Fig. 8 and Table 4 present the pertinent data.

Model Studies of the Eccentric Reducer.—Approximate results, used mainly for comparison, was the primary objective.

The model consisted of an intake box, a reducer 12 in. long with 1 in. and 2 1/2 in. diameter openings, and a 12 in. long enclosed circular channel with a 1 1/8 in. interior diameter. Both the reducer and the circular channel were tested as pipe culvert inlets. The short length of reducer (less than 10:1 for full scale inlets), within which the depth of flow changed rapidly, does not necessarily indicate that the forces of inertia and gravity predominate. Because of the small diameters, viscous forces were considered when evaluating the results, and adjustments were made before applying existing data on pipe friction factors (Table 4, column 4).

Table 4 lists the tabulated results of the test. Column 1 gives the measured discharge, and columns 5 and 6 give the observed headwater depths of the 2 1/2 in. and the 1 1/8 in. culverts for these discharges.

ANALYSIS OF RESULTS

Tapered Inlets.[2]—

Conditions Favorable for Natural Priming.—Inlet 2 (Fig. 5) is described at 4% slope as "flowing full in first the tapered section and then the culvert barrel when the rising headwater intersects the top of the entrance." At this depth, and above it inlet 2 has a noticeable increase in discharge for a small rise in headwater. It appears that air near the top of the barrel was trapped and carried away by the velocity of flow, the priming action, as indicated by the full flow, may be attributed to the condition described under "air channel block."

Inlet 4's discharge followed a pattern similar to that of inlet 2, except that priming began at a headwater depth less than the entrance depth, and the in-

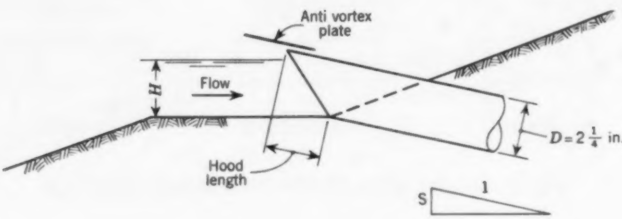

FIG. 8.—HOOD INLET MODELS

crease in discharge of this depth was more significant. Because air can enter the culvert through the outlet, it seems that the priming action is caused by the "rapid change of velocity" in the taper. This is indicated by the steeper "depth of flow" slope in the taper (line "a" Fig. 5). The steeper slope of inlet 4 is due to the greater differences in end areas of its entrance taper to that of inlet 2.

High discharge capacities for inlet 1 on a 4% grade were obtained by placing a temporary obstruction to flow at the outfall, or by inducing turbulence in the stream at the entrance. It is reported that "Inlet 1 would flow full under this condition. The contraction of stream lines at the inlet section persisted and were accompanied by a local drop in pressure a short distance beyond the entrance. This discharge would continue as long as no air was admitted to the entrance. In the natural state, however, a free vortex would form in the pool above the entrance and admit air to the inlet in sufficient quantity to allow the culvert to revert to sluice operation."

Tests on an inlet with a 1.5-to-1 tapered entrance ratio gave full flow discharge on flat slopes and sluice flow on 4% slopes. It appears that on the flat slopes, the depth of flow was sufficient to prevent air from rapidly entering through the culvert outlet, while on the 4% grade, aeration occurred

naturally, and the ratio of end areas of the taper was not large enough to cause a sufficiently steep "depth of flow" in the taper and a "rapid change in velocity" condition.

Discharge Control.—If the energy equation for the reducer discharge operation, Eq. 16, were applied to inlets 2 and 4, the control of these inlets would be at the entrance (point 1), and the discharge would approximately be equal to that of a sharp edged orifice (based on United States Bureau of Reclamation, Dept. of Commerce (USBR) 1043 criteria).

A comparison between the observed discharges on 4% slopes and the computed discharges with control at point 1 of inlets 2 and 4 for equal headwater depths (Table 1-columns 1, 2, 6 and 14), shows similar values in the median range of headwater depths, with the small differences that are probably caused by friction losses in the taper. In the upper range of headwater depths, the observed flow rates of inlet 4 were markedly less than the computed flow rates. This could be attributed to the importance of turbulence caused by high entrance velocities in the short tapered barrel, or a maximum headwater depth for effective priming.

A significant increase in discharge on headwater submergence of the entrance was measured for inlet 4, while inlet 2 showed only a moderate increase in discharge. If the analysis of subatmospheric culvert operation is correct and the control does revert from point 2 to point 1. Then the width of flow for the same headwater depth was more than doubled for inlet 4, and significant increases in discharge would seem justified. Inlet 2's width of flow was only increased by 50% and the increase in discharge is less dramatic.

There is the possibility that control remains at point 2, but with a low C_e of 0.1. Column 5 of Table 1 shows the computed discharges using this value. The observed discharges of inlets 2 and 4 were noticeably higher than these computed discharges, with the exception of the upper range of headwater depths of inlet 4 which show discharge rates comparable to the computed discharges.

Inlet 1, when primed artificially, had discharges only slightly less than those of inlets 2 and 4. Inlet 1's control could conceivably occur somewhere along its flared entrance. The high increase in discharge at depth of submergence would be caused by a situation similar to the one described for discharge control by Karr and Clayton.[3]

Inlet 4 on a flat slope did not noticeably increase its discharge until the headwater was well above the depth of submergence. This is considered the depth at which the "rapid change in velocity" was sufficient to develop voids in the taper. It seems reasonable to assume that the flat slope culvert would obtain this velocity at a greater depth than that of the steep sloped culvert because of lower entrance velocities for equal headwater depths.

The observed discharges for the $p_{a_{sub}}$ flows of inlet 4 on a flat slope were less than the observed discharges on steep slopes. If effective $p_{a_{sub}}$ is sufficiently great and control is at the entrance (point 1), the observed discharges for inlet 4 on both the flat and steep slopes should be equal. However, it is probable that separation on a flat slope had developed at points in the taper farther downstream from the entrance than when on the steep slope. The discharge was controlled by the lesser areas of the taper at these points.

Subatmospheric Pressure.—The possibility that $p_{a_{sub}}$ in the entrance of

TABLE 1.—STUDIES

Observed Discharge				Computed Discharge		Observed
4% Slope		0% Slope				
Inlet 1 Free Flow; Inlet 2 (1)	Inlet 1 Free Flow (2)	Inlet 1 Free Flow (3)	(4)	C_e = 0.1 Inlet 1 (5)	C_e = 0.4 Inlet 2 (6)	Inlet 1 Free Flow (7)
0.78	0.55			0.74	0.98	
0.70				0.61	0.79	
0.66				0.55	0.73	
0.63	0.40				0.71	
0.58	0.36			0.43	0.55	
0.52	0.32				0.48	1.03
0.46				0.32	0.40	0.86
0.40					0.36	0.69
0.27	0.24	0.24		0.20	0.26	0.42
0.22					0.22	0.34
0.16	0.11	0.12		0.11	0.16	0.27
0.08					0.08	0.17
0.55						
0.59						
Inlet 1 Free Flow; Inlet 4 (1)	Inlet 1 Free Flow (2)	Inlet 1 Free Flow (3)	Inlet 4 (4)	C_e = 0.1 Inlet 1 (5)	C_e = 0.4 Inlet 4 (6)	Inlet 1 Free Flow (7)
0.80	0.59		0.72	0.84	1.33	
0.72			0.62	0.72	1.13	
0.60				0.47	0.77	1.25
0.52	0.32		0.24	0.28	0.60	1.03
0.48					0.53	0.92
0.38					0.49	0.64
0.27	0.24	0.24		0.22	0.47	0.42
0.22		0.20		0.17	0.35	0.35
0.11	0.12	0.09		0.10	0.19	0.21
0.06				0.05	0.10	0.14
0.03				0.035	0.05	
			0.55			
			0.46			
0.55						
0.65						

Discharge - cfs H - feet

Inlet 1 Full Fl. (Artificially Prim) 4% Slope; Observed discharge for col. 8 = 0.02 ± cfs
Cols. (1 - Inlet 1 Free Fl.) 3; Observed Discharge; for col. 7.
Cols. (1 - Inlet 2, Inlet 4) 2,4; Observed Discharge; for col. 8.
Cols. 5, 6; Computed disch.; Entrance control for H col. 8; USBR 1043 C_e = 0.4; Full
Cols. 9, 10 Computed H; Entrance control for disch. col. 1; USBR 1043 C_e = 0.4; Full
Cols. 11, 12, 13a, 13.
Computed Energy based on observed pizometer readings. The readings used in Equa-
sures were observed during these runs) (Slope heads are neglected) (Observed data.[2])

Inlet 1 Full Fl. (Artificially Prim) 4% Slope; Observed disch. for col. 8 = 0.02 ± cfs less

OF TAPERED INLETS

H_h	Computed H_h		Computed Energy			Ratio
			4% Slope		0% Slope	
Inlet 1 Free Flow; Inlet 2	C_e = 0.4 Inlet 1	C_e = 0.1 Inlet 1	Inlet 1[a] Full Flow; Inlet 2[b]	Inlet 1 Free Flow	Inlet 1 Free Flow	(d) / (a)
(8)	(9)	(10)	(11)	(12)	(13)	(14)
1.08	1.92	1.20	3.05[b]			1.26
0.85		1.03	3.15[b]			1.13
0.74	1.48	0.96	3.50[b]			1.11
0.66		0.90	3.13[b]			1.12
0.58		0.81				0.95
0.52	1.02	0.72				0.92
0.46	0.84	0.64				0.88
0.43	0.70	0.56		0.68		0.90
0.35	0.44		0.42[b]	0.45	0.40	0.97
0.29	0.37		0.39[b]			1.00
0.24	0.30				0.24	1.00
0.14	0.19					1.00
			7.6[a]	1.1		
				1.1		

Inlet 1 Free Flow; Inlet 4	C_e = 0.4 Inlet 1	C_e = 0.1 Inlet 1	Inlet 1[a] Full Flow; Inlet 4[b]	Inlet 1 Free Flow	Inlet 4	Inlet 1 Free Flow	(d) / (a)
(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1.25	2.02	1.24	1.7[b]		1.2		1.67
0.99	1.65	1.07			1.0		1.57
0.60	1.25	0.84		1.09			1.28
0.43	1.02	0.72	1.25[b]				1.15
0.40	0.89	0.66		0.85			1.10
0.38	0.68	0.54	2.4[b]				1.30
0.37	0.46		0.52[b]	0.50		0.41	1.76
0.32	0.37					0.32	1.58
0.22	0.24					0.21	1.74
0.14	0.16						1.65
0.11							1.67
0.82							
0.67							
			7.6[Na]				
			8.3[Na]				

E - feet

less than col. 1 - (Fig. 6).

flow C_e = 0.1.
flow C_e = 0.1.

tion E were observed at low positive depths in the barrel E 6 d + $\frac{V^2}{2g}$. (N-Negatives pre-

than col. (a) - (Fig. 6).

inlets 2 and 4 increases the energy of flow can be substantiated by the following means:

1. Computing the headwater depth for a given discharge with an inlet 1 entrance, and comparing this depth with the observed headwater depths of inlets 2 and 4 for equal discharges.

2. Computing the total flow energy by the use of observed piezometer readings, and comparing this energy with the observed headwater depths for equal discharges.

(1) If control remained at point 2, $p_{a_{sub}}$ would not be effective in increasing the pressure in the taper entrance, and the computed headwater depth, using a value of C_e of 0.1 would be equal to, or less, than the observed depths. Column 10 shows these computed depths for inlets 2 and 4 to be significantly higher, with the exception of the upper range of depths of inlet 4.

(2) The computed energies (columns 11, 12, 13a and 13b) have no consistent pattern, probably because of the various $p_{a_{sub}}$ distributions at different depths of flow, and their accompanying friction losses. However, the computed energies are considerably greater than the observed depths for inlets 2 and 4 and inlet 1 flowing full. Thus the contention that there is a source of effective energy other than that of the headwater depth is supported.

Inlets for Pipe Culverts on Steep Grades.[3]—

Conditions Favorable for Natural Priming.—Models 4 and 6 on steep grades, and models 3, 4, and 6 (Fig. 7) on flat grades are described as "priming naturally - high velocity flow near the entrance carries away the air which has been trapped at the top of the barrel and full flow results."

Apparently, the causes for natural priming of reducers are not applicable to these models. The only similarity is the prevention of sufficient air from entering the barrel through the outlet (air channel block). The turbulence (caused by these types of entrances) and the accompanying varied areas of flow, carried away the trapped air in a manner similar to that of inlet 1's full flow operation caused by artificial turbulence.

Discharge Control.—Although the causes for natural priming of reducers are not applicable to models 4 and 6, the effects of $p_{a_{sub}}$ were similar. Unlike the tapers of inlets 2 and 4 and the 2 1/2 in. reducer, there is only one area of entrance controlling the discharges of models 3, 4, and 6. Yet, a comparison of observed discharges on steep slopes (Table 2, column 1) with computed discharges $C_e = 0.1$, column 5 for equal headwater depths, shows close correlation.

In the middle range of headwater depths, the observed discharges were slightly higher than the computed discharges, whereas, in the upper range of headwater depths, the observed discharges were slightly lower than the computed discharges. As an explanation, consider the observed significant increase in flow at depth of submergence of models 4 and 6 on steep slopes. At this headwater depth, the depth of normal flow at the entrance would be approximately 0.7 H_h, with the greater portion of the remaining area in voids. The water discharging into these voids is a separate entity from that of the normal flow (similar to reducer operation, air channel block). This high velocity of flow entering the sizable void area adds considerably to the gross discharge of the culvert. As the headwater depth increases, the normal depth of flow at the entrance becomes increasingly greater than 0.7 H_h. The area

TABLE 2.—OBSERVED DATA BY KARR AND CLAYTON

Observed Discharge				Computed Discharge		Observed H	Computed H	Computed Energy			
4% Slope		0% Slope						4% Slope		0% Slope	
Models 4, 6 (1)	Model 3 Free Flow (2)	Models 4, 6 (3)	Model 3 Free Flow (4)	$C_e = 0.1$ Models 3, 4, 6 (5)	$C_e = 0.6$ Models 3, 4, 6 (6)	Models 3, 4, 6 (7)	$C_e = 0.5$ Models 4, 6 (8)	Models 4, 6 (9)	Model 3 Free Flow (10)	Models 4, 6 (11)	Model 3 Free Flow (12)
0.17	0.17	0.10	0.10	0.15	0.13	0.31	0.35	0.45	0.58		
0.34	0.19	0.16	0.16	0.21	0.19	0.39	0.59	6.3 N		0.33	
0.40	0.26	0.26	0.26	0.32	0.26	0.56	0.68		0.56		
0.44	0.30	0.33		0.40	0.32	0.68	0.77				
0.45	0.33	0.36		0.44	0.35	0.76	0.79	9.8 N			
0.48	0.35	0.38	0.40	0.47	0.38	0.84	0.85	7.6 N	0.81	2.0	0.75 N
0.52	0.38	0.43	0.45	0.53	0.42	0.98	0.93			0.9 N	
0.54	0.40	0.45	0.47	0.56	0.45	1.06	0.99	7.3 N	0.94		
		0.48								1.9	
			0.24								0.5
			0.51								1.4 N
		0.54								1.4 N	

Discharge - cfs H - feet E - feet

Model 3 Full Fl. (Artificially Primed) 4% Slope; Observed disch. for col. 7. Slightly higher than col. 1.

Cols. 1, 2, 3, and 4 Observed Discharge; For Col. 7
Cols. 5, 6 Computed Discharge; Entrance Control for H_h col. 7; USBR 1042 $C_e = 0.5$, Ful flow $C_e = 0.1$
Col. 8 Computed H; Entrance Control for Disch col. 1; Full Flow
Cols. 9, 10, 11 and 12 - Same as for Table 1

TABLE 3.—ECCENTRIC REDUCER MODEL

Observed Discharge	Adjusted Observed Discharge	Computed Discharge		Observed H		Computed H_h		Ratio	
0% Slope Inlet 1' 8 in. Dia. Inlet 2' 2 in. Dia. (1)	0% Slope Inlet 2' 2 in. Dia. (2)	$C_e = 0.1$ Inlet 1 in. Dia. (3)	$C_e = 0.5$ Inlet 2' 2 in. Dia. (4)	Inlet 1' 8 in. Dia. (5)	Inlet 2' 2 in. Dia. (6)	$C_e = 0.6$ Inlet 1 in. Dia. (7)	$C_e = 0.1$ Inlet 1 in. Dia. (8)	$(d)/(b)$ (9)	$(d)/(b_2)$ (10)
0.007				0.11					
0.007		0.0065	0.011		0.10	0.12		1.57	
0.008	0.012	0.0075	0.013		0.11	0.135		1.63	1.08
0.014				0.20					
0.019	0.027	0.0130	0.032	0.28	0.18	0.45	0.29	1.68	1.19
0.021	0.030	0.0135	0.036	0.25	0.19	0.53	0.33	1.72	1.20
0.026	0.037	0.0155	0.046		0.22	0.82	0.48	1.76	1.24
0.034	0.048	0.0175	0.056		0.26	1.29	0.77	1.65	1.17

Discharge - cfs H - feet

Col. (1-inlet 1' 8'' Dia); observed discharge; For col. 5
Col. (1-inlet 2'2'' Dia); observed discharge; For col. 6
Col. 3, 4; Computed disch; Entrance Control for H_h col. 6; USBR 1042 $C_e = 0.5$; Full flow $C_e = 0.1$
Cols 8, 7; Computed H; Entrance Control for Discharge col. 6; USBR 1042 $C_e = 0.5$; Full flow $C_e = 0.1$
Col. 2; Adjusted observed discharge; (Approximate)

$$\frac{V_{b2}^2}{2g} - \frac{V_b^2}{2g} = h_e \frac{29 n^2}{R^{4/3}} L \frac{V^2}{2g}$$

V = Average Vel. for observed discharge
V_{b_2} = Vel. at point 2 for adjusted discharge
V_b = Vel. at (2) for observed discharge
L = 1 foot
n = 0.025 (Reynolds number adjust. of 0.015)
Area = Mean Area

of voids becomes small when compared with the flow cross section, therefore, less significant, the entrance is not tapered. Either Eqs. 3 or 16 are applicable, and the ratio of the observed to the computed flow, as can be expected, decreased with the increase in headwater depth.

The observed discharges for models 4 and 6 on flat slopes were less than the 4% slope discharges for the $p_{a_{sub}}$ range, and there were no large increases of discharges at the depth of submergence. If $p_{a_{sub}}$ sufficiently high, the observed discharges might be expected to be equal for different slopes at equal headwater depths. Consider however, the area of voids at the depth of submergence. The normal entrance depth is greater than 0.7 H_h. Thus the area of voids is smaller than the steeper sloped culverts and the gross discharge would be less. At other headwater depths the same conditions occur (probably due to lower velocities in the barrel), and the gross discharges for the flat sloped culverts would also be less than that of the steep sloped culverts, although greater than computed discharges (columns 3 and 6).

The computed energies based on the observed piezometer readings (Cols. 11, 12, 13a,13) are considerably greater than the observed headwater depths.

The discharges of models 4 and 6 reflect only a small portion of this energy, with the computed headwater depths only slightly higher than the observed headwaters for equal flows in the middle range of observations, and slightly lower than the observed headwaters in the upper range of observations.

The 2 1/2 In. Reducer.—Tabulation of observations and computations are given in Table 3.

Conditions Favorable For Natural Priming.—Both the "air channel block" and the "rapid change in velocity," the actions that cause the natural priming of reducers should apply to the 2 1/2 in. reducer.

The 1 in. diameter exit area of the reducer flowed almost completely full for all headwater depths. This exit area can be considered a point of entrance to the barrel of an imaginary culvert.

However, the almost full exit flow does not necessarily indicate the occurrence of natural priming, since the normal entrance contraction took place at the 2 1/2 in. diameter opening.

Discharge Control.—If theoretical reducer discharge operations were applied to the 2 1/2 in. reducer, the control would be at the entrance (point 1), and the flow would be approximately equal to that of a sharp-edged orifice. A comparison between the computed theoretical discharges and the adjusted, observed discharges for equal headwater depths shows close values (columns 4 and 2).

There is the possibility that control remains at point 2, but with a low entrance coefficient of 0.1. The adjusted observed discharges were considerably higher than the computed discharges for equal headwater depths (column 3). It is important to note that the unadjusted observed discharges were also noticeably higher than those computed discharges.

Subatmospheric Pressure.—The possibility that $p_{a_{sub}}$ in the entrance that increases the energy of flow was investigated by computing the headwater depth for the 1 in. opening. Columns 7 and 8 show these computed depths. Therefore, the effective energy is to be greater than the actual headwater depths for equal discharges.

Conduit Spillway Report.[4]—

Conditions Favorable For Natural Priming.—The hooded inlets are described as priming and flowing full in a manner similar to that described[3] for models 3, 4, and 6.

Discharge Control.—Regardless of the pipe slope and the hood lengths, there was a great increase in flow from the time the inlet primed until the inlet flowed full. However, the steeper the slope the greater the total increase in flow (Table 4, columns 1, 2, 3 and 4). This may be attributed to the greater available void area at the depth the inlet begins to prime, similar to that described for models 3, 4, and 6.

This report states that the laws of pipe flow control the head-discharge relationship after the culvert begins to flow full at headwater depths of 1.25 D. Yet the computed discharge (column 5) is still a good deal less than the observed flows of the steep-sloped pipes, thus indicating that effective $p_{a_{sub}}$

TABLE 4.—DATA OBSERVED BY BLAISDELL AND DONNELLY

Observed Discharge				Computed Discharge	Observed H	Computed Energy
0.025 Slope (1)	0.101 Slope (2)	0.200 Slope (3)	0.361 Slope (4)	$C_e = 0.1$ (5)	Series 56 65 82 (6)	0.025 Slope[a] 0.101 Slope[b] 0.361 Slope[c] (7)
0.09	0.165	0.24	0.32	0.09	0.38	
0.105		0.245		0.12	0.54	
	0.18		0.33	0.15	0.75	· 16 ± [c]
0.125		0.255		0.18	0.94	* 1 ± [a]
	0.20		0.34	0.20	1.10	Δ 4 ± [b]
0.14		0.26		0.22	1.31	
	0.22			0.24	1.50	

Discharge - cfs H - feet E - feet

All columns same as for Table 2.

may continue at higher headwater depths. Vortex inhibitors were shown to be effective.

Subatmospheric Pressure.—Negative pressures were recorded near the entrance. The computed energies are considerably greater than the observed headwater depths (Table 4, column 7).

CONCLUSIONS

These conclusions are based on the results of preliminary reducer model tests, and on the results of small models tested by others. The entrance of these other models were essentially different in shape from that of the reducer entrance. Extreme caution should, therefore, be used in the application of the design principles expounded herein.

Natural priming will occur in a reducer entrance. The minimum headwater depth at which this will occur is 1.3 D_2 for design application (Fig. 1). The maximum depth could not be established.

Although effective vortex inhibitors can be installed on reducer entrances, this should be unnecessary, since a lateral enlargement of the inlet to twice the barrel width will give a velocity of flow in the inlet vicinity insufficient to produce more than desultory circulation and vortex formation.[5] In addition, the natural separation will occur in the tapered barrel as well as at the entrance, or well beyond the penetration point of a vortex.

The reducer entrance will permit an efficient conversion of $p_{a_{sub}}$ to effective discharge energy. The extent of this effective pressure could not be established.

Discharge through a reducer entrance within the appropriate range of taper sizes and headwater depths can be based on the large opening and the headwater depth at this opening. Because no accurate relationship was established between theoretical discharge with control at the entrance (point 1), and actual discharge with control at point 1, or between theoretical discharge with control at some intermediate point between points 1 and 2 and actual discharge at this intermediate point, realistic entrance coefficients need to be established. The separate discharge into the voids can be neglected because the volume will be small.

The following criteria are suggested as a guide for further testing: (Figs. 1a, 1b, and 1c)

1. Solution "A"
   USBR Standards; Control at (3);
   Chart 1041, 1042; min $H_h = 1.3\ D_2$, max $H_t = 1.2\ D_2$
   Step (a) For design flow determine headwater depth for pipe length L, pipe diam D_2; Chart 1041, Coef 0.1
   (this headwater depth is the effective subap)
   (b) For 1.2 design flow determine headwater depth for pipe diam D_1; Chart 1042, Coef 0.5
   (this headwater depth is the design depth)
   (c) Arbitrary limit
   Max (a) = (b) + 4 ft
2. Solution "B"
   USBR Standards; Control at (2);
   Chart 1041, 1042; min H = 1.3 D_2, max TW = 1.2 D_2
   Step (a) For design flow determine headwater depth for pipe diam D_2
   Chart 1042, Coef 0.1
   (this headwater depth is the effective subap)
   (b) Same as Solution "A"
   (c) Same as Solution "A"
3. Reducer Sizes that Will Prime Naturally
   Max Taper; 5 in 12: Min Taper; 1.5 in 12
   Max entrance opening; 2 times pipe culvert diameter

To summarize then, the overall advantages of the prefabricated reducer as an entrance for a pipe culvert are as follows: (1) Natural freedom from

[5] "Hydraulics of Box Culverts," by D. E. Metzler and H. Rouse, Bulletin No. 38, State Univ. of Iowa, 1959.

serious vortexs, (2) Avoidance of the accumulation of debris, (3) Economy, (4) Low entrance losses, and (5) Predictable flow rates in the subatmospheric range.

APPENDIX.—NOTATION

The following symbols, adopted for use in this paper, conform essentially with "American Standard Letter Symbols for Hydraulics" (ASA Z10.2-1942), prepared by a committee of the American Standards Association with Society representation, and approved by the Association in 1942:

C_e = coefficient of velocity head representing the loss of head at the entrance;

D = depth of flow in pipe;

d = diameter of pipe;

E = energy;

f = friction factor;

H_h = headwater elevation or depth above inside bottom of pipe at entrance, in feet;

H_t = tailwater elevation or depth above inside bottom of pipe at outlet, in feet;

h_e = represents the loss of head through the pipe culvert;

L = effective length of pipe culvert, in feet;

n = roughness coefficient;

p_a = atmospheric pressure, in feet;

$p_{a_{sub}}$ = subatmospheric pressure, in feet;

$p_{ae_{sub}}$ = effective subatmospheric pressure at small end of reducer, in feet;

p_{s_I} = instant static pressure, in feet;

p/w = static pressure head, in feet;

S = slope of pipe culvert, in feet per foot; and

V = mean velocity.

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EARTHWORK COMPUTATIONS ON ELECTRONIC COMPUTERS

By Robert J. Hansen,[1] M. ASCE, S. Ray Cason,[2] M. ASCE, and Paul Yeager[3]

SYNOPSIS

Described is the complete system of earthwork computations being used presently. Included is a description of the basic earthwork quantity calculations, machine-computed template notes (including median design), and the by-products which are providing additional services to the engineer.

INTRODUCTION

Engineers who are unfamiliar with the computer processes of earthwork computations have been led to believe that only earthwork quantities are being computed. Computers were justified in state highway departments on the basis of earthwork quantity calculations and programs to do this type of processing were generally the first to be adapted by highway engineers. However, through evolution, development progress, and the availability of machines for the addition of other techniques to the process, the quantity calculations have become only a small part of the integrated system.

As computers were introduced, engineers were confronted with new methods of approach to design the most economical highway. Now as computers are being used and reams of computed design data is made available, the engineer also must understand the machine system for the most efficient utilization of computers.

Note.—Discussion open until August 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. HW 1, March, 1961.

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During the past four-year period (1956 through 1960) there has been a concentrated effort by all highway engineers in the computer field to develop and improve computer uses. This has been especially true and necessary for earthwork computation. The typical earthwork problem is not merely the balancing of cuts and fills for a two-lane road as discussed in most textbooks or illustrated in sample problems. The multi-lane freeway is now the common type of roadway being designed and therefore has been the determining factor in approaching the problem.

The complete machine system has been developed through a series of building blocks. Each block represents a computer program and another service to the engineer. It will be noted that flexibility has been stressed and a standardized method adopted. The complete system may be used for reconnaissance, design or construction computations, or it is possible to use only part of the system, as needed.

THE BASIC PROCESS

From the very beginning of engineering, the problem of finding the amount of excavation and embankment that will occur during the construction of any earth-moving project has been solved in much the same way. Some base or center line was established and along this line "stations" were marked off and the "elevation" of these stations above some reference datum was determined. Distances along transverse lines at each station out from the center line and elevations above or below the center-line elevations were taken at every point where there was a change or "break" in the ground surface. These measurements describe a "cross section" of the original ground.

A grade line would then be established along the center line at the surface of the finished project. The desired width and shape of the finished excavation or embankment (in the case of a highway or railroad, the width of the roadway, the size of the ditches, and the slopes of the cuts and fills) would be decided on. The finished shape, being more or less uniform throughout the project would be referred to as a "template."

Now, if the cross section of the original ground and the template of the finished project were brought together, an area of excavation or embankment would be defined at that station. When this area of cut or fill was calculated, averaged with the corresponding area at the next station, and multiplied by the distance between the stations, the result would be the volume of excavation or embankment between these two stations. This is the basic method of computing earthwork quantities.

An electronic computer program, if it is to be generally useful and capable of being adapted to all of the various special requirements of all projects, must closely follow basic methods, particularly in regard to input and output. That this can be done with the modern high-speed computer is shown in the following description of the computer process of computing earthwork quantities:

Input.—In using the computer to compute the volume of earthwork, the two basic types of data previously described are supplied by the field or design engineer. These "cross-section notes" and "template notes" are essentially the same data as that used in manual computations.

Cross-Section Notes.—Cross-section data defines the original ground surface. It consists of the station number, to show the position of the cross section along the center line, the reference elevation, above some datum plane,

and a series of measurements. These measurements, which shall be referred to as readings, are actually the x and y coordinates of points on the surface of the original ground and are usually written in the form YYY.Y/XXX.X, where YYY.Y is the distance above or below the reference elevation and XXX.X is the distance out left or right from the center-line. The reference elevation may be either the height of the instrument (HI), the elevation of the ground at the center line or any convenient reference, such as an even elevation above sea level.

Cross-section notes may be of two types, depending on the use to be made of them. On a design project the readings extend far enough out on the left and right of center line to be well beyond the "catch points." "Catch points" are the intersections of the finished excavation or embankment slopes with the original ground.

The second type of cross-section notes are those prepared for a job already staked or constructed where all of the readings, including catch points, are known. The readings then would extend from the left catch point to the right catch point. The reason for and use of each of the two types will be more completely explained under the heading "Determination of Quantities."

Cross-section notes may be prepared by field crews taking readings directly on the ground, from previously prepared contour maps, or directly from stereo pairs of aerial photographs.

Template Notes.—Data given in the template notes define the shape of the finished excavation or embankment. This follows, more or less, a typical section and there are many ways of expressing template notes, such as by crown slopes and distances, ditch depths and widths, etc. However, for ease in the preparation of the notes by the engineer and to make the computer method of computation as flexible as possible, the best way to write template notes is to use a coordinate system the same as that used for cross-section notes.

A template, then, consists of a set of x and y coordinates of a sufficient number of points to accurately describe the surface of the finished project. To completely define an area, there must be template notes at every station where there are cross-section notes. The reference elevation for the template notes is usually the elevation of the finished grade at that station. The readings will begin at the left catch point and, following the shape of the finished section, proceed across the center line to the right catch point.

On a design project, the point at which the proper cut or fill slope will intersect the ground is not immediately known but can be evaluated. In this case the electronic computer is allowed to find the intersection. Instead of giving the catch point for the left-most reading, the desired slope is given. Slopes are designated in terms of the number of feet horizontally for 1 ft vertically. The second point would be the coordinates of the "hinge point" of this slope. In a like manner, the next to the last reading would be the right "hinge point" and the last reading would be the desired slope on the right.

There is another advantage, not readily apparent, in using slopes instead of catch points and allowing the computer to determine the point of intersection during the earthwork-computing process. In the design stage, it is almost always necessary to make some changes in the finished grade line. This can be easily accomplished by merely changing the reference elevation. Since slopes only are specified and the catch points are recomputed each time by the machine, it is not necessary to make any changes in the template notes other than the elevation. This results in a saving of hand work when making grade changes.

Thus there are two types of templates, those made up entirely of x and y coordinates of the finished section and those whose first and last "readings" are actually slopes to be used by the computer to find the catch points.

Template notes may be hand written by the engineer for each section. This allows him complete flexibility in that he can specify any desired shape of excavation or embankment, from a footpath to a major airport landing strip. In the construction of highways, however, there are vertical curves in the grade, horizontal curves in the alinement which require superelevation and its associated transitions from crowned to superelevated sections, and varying depths of cuts and fills that require different slopes. For these conditions, the hand preparation of template notes becomes very tedious and time-consuming. This difficulty can be eliminated by allowing the computer to prepare the template notes. This very efficient and time-saving feature will be explained subsequently.

To summarize, at every station two types of data are required as input to the computer: "cross-section notes" to define the original ground and "template notes" to define the finished construction. These two sets of data may be prepared in various ways and, when brought together, enable the computer to determine volumes of cut and fill.

A typical example of cross section notes is shown in Fig. 1; template notes are very similar.

Determination of Quantities.—Although what goes on in the computer while it is computing earthwork quantities is of little interest to the engineer, a brief explanation of the process may tend to dispel the mystery which seems to surround all electronic computation. Everything the computer does can be done with pencil and paper and the methods followed in a computer "program" are quite often the same as hand methods.

Several methods of computing the volumes of earthwork using electronic computers have been developed. A basic program that has had wide usage is one written by J. M. Kibbee and J. W. Robinson for the International Business Machines Corp. and will be the one described here. Programs written by others may differ in detail, but are basically the same.

Computation of Area.—The readings in the cross section and template notes at each station are first read into the machine and stored in its "memory." To eliminate negative values in the x-coordinates the distances to the left and right of the center line are modified so that they are references to a line 1,000 ft to the left of center line. For each station, a table is set up which contains the x and y values of all the readings on the original ground (cross-section notes). A table is also set up for the x' and y' values of the final section (template notes), either directly from the data given or, if the outside readings were slopes instead of catch points, an independent computation is made to determine the coordinates of these points and they are inserted in their proper place in the tables. Thus we now have a complete coordinate description of an end area. If the values in the two tables were superimposed on each other, they would result in Fig. 2. The solid lines represent the original ground and the broken lines the completed section.

The method of computing areas in the program being described is by a series of triangles and trapezoids. Therefore it is necessary to find the length of the parallel sides and the normal distance between them. Since readings are not usually taken at the same distance out from center line on both the cross-section notes and template notes, additional readings are interpolated by the

P SH NO. 1 PROJECT NO. L-1940
SECTION HIGH BRIDGE TO LOW CK.

EARTHWORK DATA

LINE DESIGNATION L DISTRICT NO. 8

ROD READINGS ☐
ELEVATIONS ☐
+OR-ELEV. @ ℄ ☒
+OR-ELEV. @ ___ ☐

CROSS SECTION NOTES ☒
TEMPLATE NOTES ☐

DATE 6-27-57 PAGE 1 OF 1
PARTY CHIEF SMITH
RECORDER JONES

STATION	+	LEVELS BS +	HI	FS −	ELEV.															
989	60				1168.03					$+134^{2}$	$+81^{1}$	0^{0}	20^{5}	75^{6}						
										100	50	0	50	100						
999	00				1170.91					$+141^{1}$	$+78^{2}$	0^{0}	18^{5}	23^{6}	42^{3}					
										100	50	0	31	50	100					
1000	00				1171.10					$+135^{6}$	$+77^{4}$	0^{0}	15^{2}	23^{6}						
										100	50	0	50	100						
1001	00				1180.00			$+123^{7}$	$+106^{5}$	$+90^{5}$	$+75^{3}$	0^{0}	08^{2}	25^{1}	31^{3}					
								100	65	57	50	0	30	50	100					
1001	50				1181.01					$+110^{8}$	$+71^{4}$	0^{0}	05^{1}	07^{3}	08^{2}	10^{6}				
										100	50	0	25	30	50	100				

FIG. 1.—CROSS-SECTION NOTES

program and inserted in the tables so that for every cross-section reading there is a template reading directly above or below and the same is done for each template reading.

It is now an easy matter to compute the areas and combine them together to obtain the total areas of cut and fill.

Computation of Volume.—The volumes of cut and fill are computed by the familiar "average end area" method. The total cut area at one station is averaged with the total cut area at the next station to obtain the average cut end area. The same is done for fill areas. These average areas are then multiplied by the distance between the stations to obtain the volumes of cut and fill.

At this point it is convenient to apply the shrinkage or swell factors to the embankment or excavation quantities. Either the cut volume or the fill volume may be multiplied by a factor, depending on the requirements of the user.

The final output, then, is an adjusted fill volume, an adjusted excavation volume and such other data as may be considered useful. This will be explained under the heading "Output."

Computation of Slope Intersection.—When the location of the catch points is not known, as in the case of a design project, and the first and last readings of the template notes are given as slopes instead of coordinates of points, it is necessary for the computer to determine the catch points.

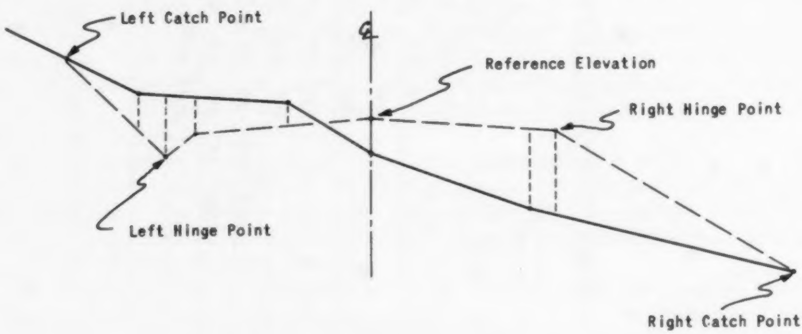


FIG. 2.—END AREA

The arithmetic computations involved are quite simple. The computer, having been given the slope, merely extends it upward or downward from the hinge point until it intersects the ground line. The coordinates of this intersection define the location of the catch point.

If the cross-section notes do not extend out far enough and the intersection with the original ground line cannot be found using the slope specified the computer connects the hinge point with the last cross section reading and uses this line as the boundary of the area. The fact that this non-standard slope has been used is indicated in the output.

Although the computation of the catch point by using a given slope is simple, the determination of the proper slope to use is much more difficult. The choice of slope depends on many factors as, for example, whether the section is in cut or fill and the depth or height of each. This choice of slope has been set up as a separate operation and will be explained under the heading "Slope Selection."

Output.—The output of the computer program, to be useful to the engineer, must be simple, complete, and in a form similar to that with which he is familiar. An example of an acceptable form of output is shown in Fig. 3.

Cut and Fill Quantities.—The main objective of any earthwork program is the volume of cut and fill involved. In the example, these quantities are listed under their respective headings opposite the station number. The volumes shown are in cubic yards and are the quantities between that station and the preceding station. At each station ending in zero there is a "ten station" total of cut and fill, useful for summation purposes.

At the upper left of the sheet there is an identifying job number and date. Just to the right of the station listing, under "ELEV," is printed the reference elevation at that station. This is the reference elevation used on the template notes.

Adjustments for Shrinkage or Swell.—To the right of the cut and fill columns in the example is a column headed "ADJ FILL." It is the practice of some to apply shrinkage and swell factors to embankment quantities only, as is the case here. For other users this could be modified to apply shrinkage to embankments and swell to cuts or to use any other method necessary to conform to particular specifications.

The shrinkage and swell factors are supplied to the computer together with the station limits between which each is to be applied and are stored in its "memory" to be used as required.

Incorporation of Additional Quantities.—It is often desirable to introduce into the earthwork computations certain additional quantities of cut and fill. There may be many reasons for this, such as the inclusion of side borrow or waste, approach roads, etc.

These can be included and will be listed under "ADD C & F." Although these quantities can be introduced directly into the electronic computer program, it often results in a more flexible arrangement to include them later, such as during the printing of the output on the tabulating machine.

Mass Ordinates.—Generally it is necessary to prepare a mass diagram so that any overhaul on excavated material can be computed. To aid in this process, the next column on the example contains, under "MASS ORD," an accumulative total of adjusted cut and fill quantities. These are the ordinates to be used in the construction of a mass diagram.

Again, it has been found to be more flexible to do this summation on the tabulating equipment, although it is entirely feasible to use the electronic computer for this.

Slope-Stake Data.—On the right-hand side of the output sheet are two similar groups of three columns each. These contain the data on the catch points. The first column of each shows the slope used and will conform to the input data except in the case where the cross-section notes were inadequate. As mentioned before, this will then contain a non-standard slope and an indicating mark will be printed under "LT CD" or "RT CD," for left code or right code, respectively.

The second column of each group contains the y-ordinate of each catch point. In more common terms this is the amount of cut (C) above the reference elevation or the amount of fill (F) below the reference elevation.

The third column, the x-coordinate, is the distance out from center line to the catch point.

It should be noted that the output sheet presents the data in an orderly manner and in the same form as that used by all engineers. The only new thing

	STA	ELEV	CUT	FILL	ADJ FILL	ADD C & F	MASS ORD	LT CD	LT SLOPE	LT Y	LT X	RT CD	RT SLOPE	RT Y	RT X
■ L 2487	90+00	1372.80							4.0/1	.3F	41.4		4.0/1	2.0F	34.4
■ 3/04/60	91+00	1373.20	297	2	3		294		4.0/1	.2C	43.0		4.0/1	.6F	40.0
■	92+00	1373.60	316	10	13		597		4.0/1	.6C	44.7		4.0/1	1.2F	37.5
■	93+00	1374.42	243	35	46		794		4.0/1	.1C	42.8		4.0/1	1.7F	35.7
■	94+00	1376.08	144	139	181		757		4.0/1	1.0F	38.6		4.0/1	2.1F	33.1
	94+00					5432C	6189								
■	95+00	1378.16	46	313	407		5828		4.0/1	3.5F	28.4		4.0/1	4.3F	35.9
■	95+50	1379.20	1	160	208		5621		4.0/1	3.2F	30.3		3.0/1	5.3F	35.1
■	96+00	1380.24	24	85	111		5534		4.0/1	2.6F	33.7		4.0/1	4.8F	39.3
■	96+50	1381.28	297	24	31		5800		3.0/1	4.7C	54.3		4.0/1	.3F	37.6
■	97+00	1382.32	850				6650		1.8/1	13.3C	59.4		4.0/1	1.2C	43.6
■	97+50	1383.36	1231				7881		1.8/1	16.7C	65.5		4.0/1	1.5C	45.0
■	98+00	1384.40	1440				9321		1.8/1	17.6C	67.1		4.0/1	1.9C	46.5
■	98+50	1385.44	1615				10936		1.8/1	18.6C	68.8		4.0/1	2.3C	47.9
■	99+00	1386.48	1690				12626		1.8/1	18.4C	68.4		3.0/1	4.2C	48.5
■	99+50	1387.52	1832				14458		1.8/1	20.2C	71.7		3.0/1	4.3C	48.9
■	100+00	1388.56	1963				16421		1.8/1	19.2C	69.9		3.0/1	3.4C	46.3
	TEN STA TOTAL		11989	768											
■	100+50	1389.60	1956				18377		1.8/1	21.6C	74.2		3.0/1	3.8C	47.4
■	100+90	1390.43	1547				19924		1.8/1	20.9C	73.0		3.0/1	3.2C	45.8
■	101+00	1390.64	356				20280		1.8/1	18.5C	68.6		4.0/1	2.1C	47.3
■	101+50	1391.68	1076	5	7		21349		3.0/1	4.3C	53.2		4.0/1	2.2C	47.5
■	102+00	1392.72	345	14	18		21676		4.0/1	.6F	42.1		4.0/1	.2C	39.7
■	102+50	1393.76	110	131	170		21616		4.0/1	.3F	43.0		4.0/1	3.5F	34.3

FIG. 3.—EARTHWORK ANSWER SHEET

about the form, except that it is printed instead of handwritten, is the inclusion of the catch point data. This, however, is listed in a logical manner and the engineer soon becomes accustomed to it and to its uses.

Uses of Output.—Aside from the obvious uses of the output tabulation for giving volumes of cut, fill, adjusted cut or fill, and the mass ordinates, there is other useful information on this sheet.

For example, a check of the "SLOPE" columns will quickly indicate any sections where the cross-section notes were inadequate. Also from these columns it can be seen if the slopes are varying too much from station to station. (This may be due to varying heights of cuts or fills where strict adherence to specifications must be overridden manually.)

To correct either of the foregoing conditions or, more generally, to correct any difficulties or make changes, it is customary for the engineer to make the required changes with a colored pencil on the printed listings of the cross-section notes and the template notes which are always furnished to him in addition to the regular output sheets. These indicated changes are made and the job recomputed. The final result is an accurate and complete set of earthwork computations.

Other useful information may be found on the output sheet by scanning the y-ordinate column. The points of greatest fill will probably indicate the correct location for drainage structures, pipes, etc. This information can be more completely and accurately used by plotting a profile of the catch points on either side. These profiles, called "catch-point profiles," are a comparatively new technique in the design of highways. When plotted compositely with the original ground and the grade line along the center line, they provide very useful material to aid the designer in laying out drainage, special ditches, road approaches, etc.

To facilitate the manual plotting of "catch-point profiles," it is possible to have the electronic computer convert the catch point y-coordinates from distances above or below the reference elevation to actual elevations. Machine plotting of the plan and profile view of catch points is discussed under the heading "By-products of Output Data."

A very obvious use of the y-coordinates of the catch points is in determining right-of-way widths. Since these distances define the limits of construction on each side of the center line, the minimum width of right-of-way required can be found by scanning these columns. Again, the plotting of these points will give better use of the information and can be plotted either manually or by machine.

Another important use of the catch-point coordinates on the output sheet is in the field work of setting control or "slope stakes" for the use of the people doing the actual construction. It is customary to set stakes at the top of the cuts and at the toes of the fills, marking these with the "cut" or "fill" and the distance from the center line. The vertical reference on these stakes is usually referred to some point other than finished grade at the center line. If the computer uses the proper point as a reference, as is customary, the catch-point data on the earthwork output sheet would be exactly the same as that required on the slope stake.

If accurate preliminary cross-section notes are taken, time is saved in slope staking with the aid of machine-computed catch points. The horizontal distance as computed is used to locate the approximate slope-stake point and a rod reading is taken there. If the rod reading agrees with the machine computed catch point, the slope stake is set at this point. Where the rod reading

does not agree only a slight adjustment will usually be necessary. This results in considerable time saved over ordinary "try, compute and try again" methods of setting slope stakes.

Finally, the earthwork output tabulation, being neat and legible, is ideal for filing away as the final records for the project.

BY PRODUCTS OF BASIC MACHINE PROCESS

Once information is recorded on data-processing cards or tape for earthwork quantity processing, other uses or analyses can be made of the data. This is true both for input and output data. By-products of the basic earthwork program, through normal building-block processes, have resulted in nine computer applications, each of which provides an added service to the engineer.

The flow of data from one phase of the system to another is shown in Fig. 4. Note that cross-section notes may be converted by three methods; namely, (1) elevation reduction, (2) contour interpolation, and (3) line shift. Also template notes can be superimposed on cross-section notes for stage construction type projects.

The answer cards from the earthwork computations provide sufficient data for the following additional programs: (1) overhaul computations, (2) slope-stake elevations, (3) grass-seeding quantities, (4) mass-ordinate plot, (5) plan and profile plot of slope stakes.

Elevation Reduction.—Cross-section notes are plotted for up to 5% or 10% of the total sections that may have unusual conditions. Because of the difficulty in plotting notes that are expressed in rod readings or plus or minus readings from center line, these readings, at the request of the engineer, are converted to elevations. Input data consists of cross-section notes in the form required for earthwork processing and the output consists of elevations in a form also suitable for input to the earthwork computations. Slope-stake data expressed as plus or minus readings from the reference elevation can also be converted to elevations on tabulating machines at the request of the engineer.

Contour Interpolation.—Special contour maps are often prepared for bridge sites and interchange areas from cross-section notes taken in the form of rod readings. These contour maps are usually drawn with a 1 ft or 2 ft contour interval. Because of the time-consuming task of interpolating elevations between ground breaks, the cross-section notes which will be used for earthwork computations are interpolated and expressed as contour elevations at their respective distance out from center line. Contour intervals from 00.01 ft to 99.99 ft may be requested by the engineer; however, the most common requests are for 1, 2, and 5 foot intervals.

This program has also been used to determine the location of contour intervals along ramps expressed as stations in the preparation of contour maps to illustrate the design topography of interchanges. This is accomplished by submitting the profile grades of ramps written in the form of cross-section notes. The location of the contour interval on the answer sheets is expressed as the horizontal distance from the center line and for this type of problem the center line is assumed to be the beginning point of ramp.

Line Shift.—Cross-section notes submitted for earthwork computations are referenced to some known base line. The base line is normally a so-called "P" line, an "L" line, or, in the case of stereo maps, can be the center line or border of the area to be investigated. To present computed answers in the

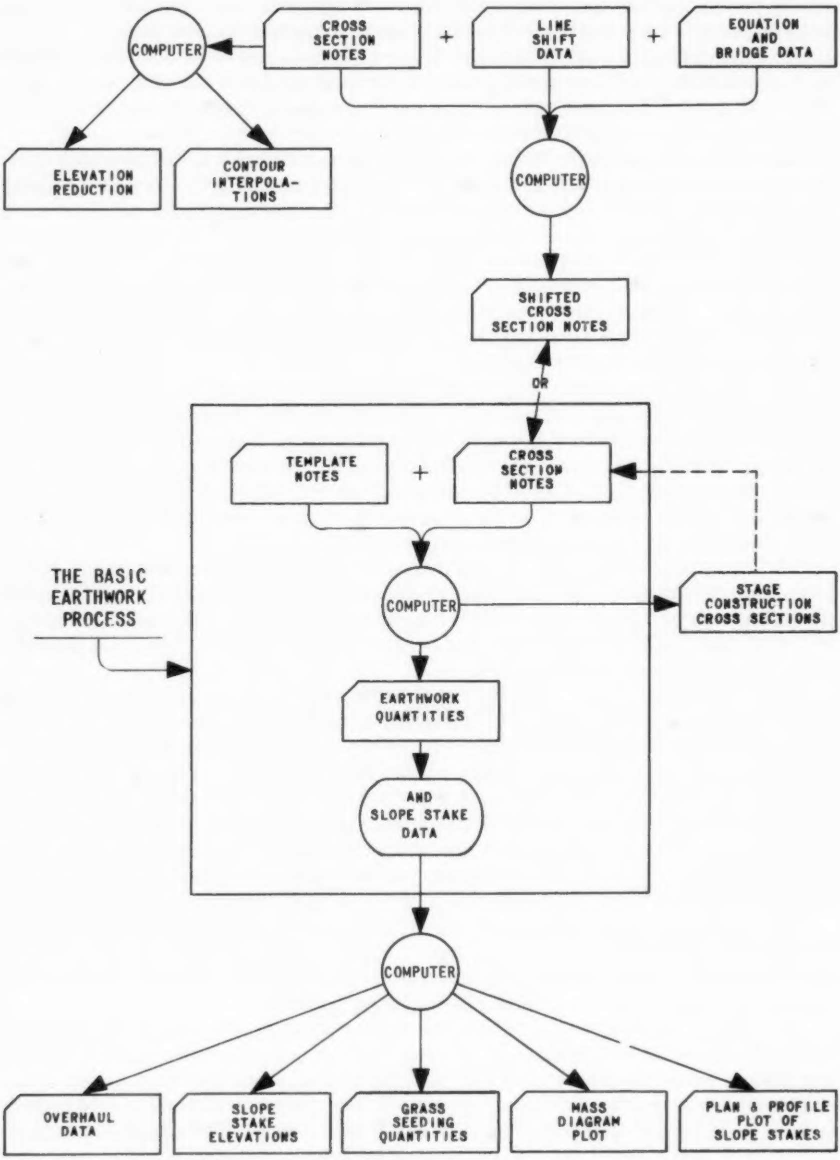


FIG. 4.—COMPUTATION OF EARTHWORK QUANTITIES AND BY-PRODUCTS OF BASIC MACHINE PROCESS

most usable form and to provide the engineer with cross-section notes based on the center line of the roadway under investigation, the cross-section notes are converted to a format as if taken from the roadway center line.

A rod reading is interpolated at the roadway center line location and the horizontal distances are expressed as distances out from the new center line. This conversion has been called "line shift" because, in effect, the center line base line is being shifted to a new location.

There are several conditions that must be considered in a line-shift program since a new line will not always be of the same length nor parallel with the base line. Generally there are also station equations to be considered in either or both lines. Since these conditions are common, the line-shift program was developed with flexibility to handle these conditions. For variable shifting distances and changes of station between designated beginning and ending points, a straight-line interpolation method is used. Also, given the back and ahead station of an equation, the program will incorporate the equation data into the straight-line interpolation.

The line-shift program is not only a valuable tool for adjusting an alinement horizontally, but is used extensively in the processing of multi-lane freeways. To reduce field and office time, it is recommended that cross-section notes be taken from one base line for multi-lane facilities even though there may be independent alinements. The independent alinements must, however, be in close proximity to one another. The original cross-section notes can then be shifted to each alinement for subsequent computations.

The same input data, that is, stations and offset distances, required for the line-shift program is also used in the design of medians. Similar techniques in each phase of the system reduce the amount of data required for computation and also make it easier for the engineer to submit the data. Median design will be discussed subsequently.

Stage Computation of Cross-Section Notes.—On most construction projects there are areas where separate quantities of various materials must be computed for the determination of payments to the contractor. An example of separate quantity computations is the excavation of unsuitable material, partial backfill in excavated area with selected borrow material, and the remaining area backfilled with unclassified material. This example is shown in Fig. 5. To adjust the cross-section notes for each computation, the template notes are, in effect, superimposed onto the cross-section notes, resulting in a revised set of cross-section notes which describe the new topography.

The method of stage computation of cross-section notes for the computation of separate quantities may also be used for temporary detours, frontage roads which intersect back slope of main line, rock with over-burden, berms, and riprap, in addition to the unsuitable-material problem.

Overhaul Computations.—Since overhaul computations can be computed from stationing and mass ordinates, it follows that the output answer cards from the earthwork program can be used for the determination of overhaul units. Limitations may arise, depending on the size of the computer and the incorporation of free haul areas. For a medium size computer with 2,000 words of storage, it has been found that locating and computing free-haul units must be excluded due to the unlimited number of configurations to be considered. The practical use of free haul in present-day highway design is also questionable; therefore, the program as now exists excludes free-haul computations.

All of the data found on a mass diagram, excluding free haul, are calculated on the computer. This includes overhaul units as well as direction of haul tabulated by stations. Here again the tabulation of results must be presented in a format acceptable to the engineer. In this way, the plotting of mass ordinates can be eliminated with an appreciable saving in time. The tabulation of results is shown in Fig. 6.

The method of computing overhaul units differs between design and construction projects. For design, the engineer will furnish shrink and swell factors and the computer will determine the balance points. On construction, the

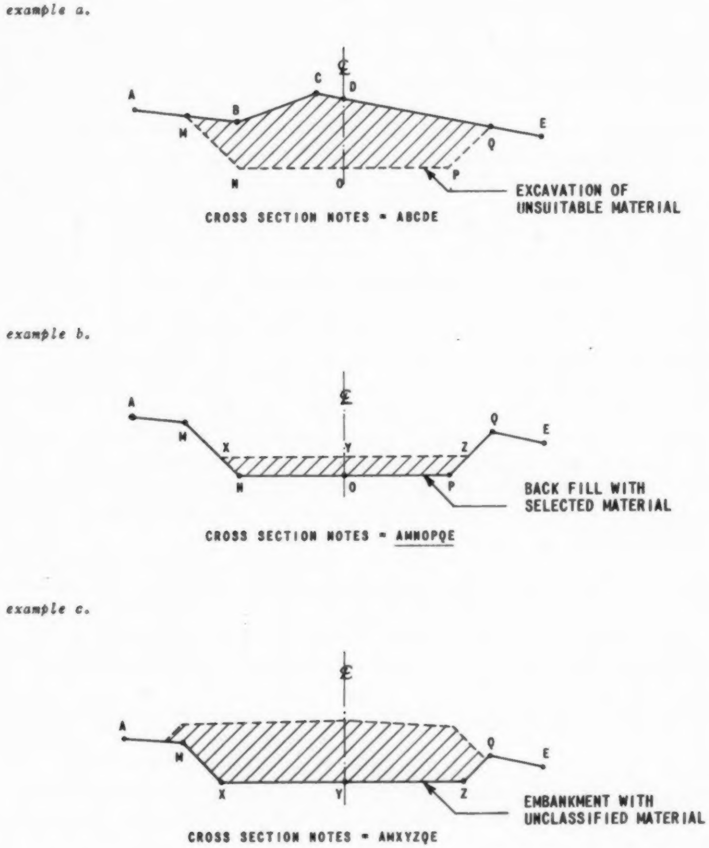


FIG. 5.—STAGE COMPUTATION OF EARTHWORK QUANTITIES

process is reversed for the engineer furnishes the balance points determined by the grading inspector and the computer will determine the combined average shrink or swell factor between balance points and adjust the mass ordinates accordingly.

PROJ. NO.	DATE	STA.	CU. YD. EXCAV.	EMBANK. PLUS	EMBANK. FACTOR	MASS ORD.	UNITS OF OVERHAUL	DIRECTION OF HAUL
1919-2	4/07/60	17+00	5	404	1.2000	22061+		AHEAD
		18+00	5	668	1.2000	21398+		AHEAD
		19+00		2653	1.2000	18745+		AHEAD
		20+00		3673	1.2000	15072+		AHEAD
		21+00	384	680	1.2000	14776+		AHEAD
		22+00	3137	44	1.2000	17869+		AHEAD
		23+00	1839	346	1.2000	19362+		AHEAD
		24+00		6953	1.2000	12409+		AHEAD
		25+00		11943	1.2000	466+		AHEAD
		25+05		466	1.2000	+	3953	AHEAD
		25+05			1.2000	+		AHEAD
		26+00		8397	1.2000	8397-		BACK
		27+00	496	2844	1.2000	10745-		BACK
		28+00	4455		1.2000	6290-		BACK
		29+00	3487		1.2000	2803-		BACK
		30+00	2186		1.2000	617-		BACK
		30+56	617		1.2000	+	285	AHEAD
		30+56			1.2000	+		AHEAD
		31+00	501		1.2000	501+		AHEAD

FIG. 6.—MASS-DIAGRAM TABULATION

Mass-Ordinate Plots.—It was noted previously (under the heading "Overhaul Computations") that the plotting of the mass diagram could be eliminated. Since some resistance to change usually exists, a program has been developed and made available to the engineer to arrange data on cards for the automatic plotting of mass diagrams. Ordinates to the curve are represented by tabulating a number (symbol or decimal) as a point on the curve. The engineer is required to draw the line between each tabulated ordinate.

Plotting of mass diagrams should not be recommended in the future either manually or mechanically. Manual plotting consumes time that could be used for more productive use, and mechanical plotting will provide the engineer with an additional set of analysis sheets with the same data that can be presented and utilized more efficiently on the tabulation of the overhaul computations. The contractor's use of the mass diagram can also be eliminated with the use of mechanically plotted plan and profile views of slope data, which is discussed subsequently.

Plan and Profile Plot of Slope Stakes.—In the era before computers when design engineers, from necessity, had to plot and planimeter cross sections for the determination of earthwork quantities, it was a common practice also to plot a plan view of the slope stake points and center line or roadway. This was done to determine right-of-way limits as well as to provide a useful tool to determine drainage needs. By incorporating the profile view of the same three lines on the sheet below the plan view, the sketches would provide a three-dimensional view of the roadway which plotted cross sections could not portray.

The conversion to computer methods does not eliminate the need for plotting the plan and profile lines of catch points. Since the data and machines are available to provide this design tool mechanically, a computer program was developed. The computer program again makes use of the earthwork answer cards which provide the station, profile grade elevation, and the x and y ordinates of the slope stakes referenced to the profile grade. The program merely determines the arrangement of the three points on a data-processing card for tabulation, one card each for the plan and profile plot at each station and the +50 station. The card columns represent a predetermined horizontal scale for the plan view plot, together with space for station.

For the profile plot, the card columns represent a predetermined vertical scale and space for the station. The location of the three punched holes on the cards for each of the two types of plots is determined on the computer. In the case of the profile plot on steep grades, there is an automatic adjustment or shifting of half of the scale to keep the plotting within the width of the paper. To maintain a true longitudinal scale on the tabulated paper, there are output cards for each +50 and even station.

To distinguish the lines on the profile plot, a 1, 2, and 4 are tabulated to indicate, respectively, the profile grade, left slope stake, and right slope stake. Where lines intersect such as the 2 and 4 lines, a 6, which is the sum of codes 2 plus 4, is printed to indicate the intersection. The sum of the other combinations of intersecting lines is also printed for an intersection indication.

A number code is also used in the plan view plot. Numbers 3 and 5 represent cut sections and 2 and 4 represent fill sections. The plan view plot is especially useful for the plotting of multi-lane freeways with independent alinement. Where the slope points of each roadway overlap in the median, the need for complete grading of the median is recognized readily. The tabulation in this case would provide the engineer with an easy method to determine the beginning and ending stations of section where the median must be designed by

the computer. Median design on the computer is discussed in one of the following sections.

The tabulated plots of the plan and profile of slope stakes are shown in Figs. 7 and 8. The mass-diagram plot is shown in Fig. 9. Fig. 6 shows the overhaul listing for part of the mass diagram in Fig. 9.

Grass-Seeding Areas.—The computation of grass-seeding areas is also available from data previously punched on cards or tape. This program requires template notes and the answer cards from the earthwork computations for the determination of grass-seeding areas. Areas are computed on the plane of the slopes and provide the engineer with both area and cubic yards of top soil by station and the accumulated totals of each. The engineer, when requesting this type of processing, must provide the beginning and ending station of section as well as job number and data of earthwork processing records to be used.

MACHINE COMPUTED TEMPLATE NOTES

Writing template notes manually is time consuming, costly, and subject to errors, therefore, a computer program that produces template notes is required in a completely mechanized earthwork process. The same basic data that is used to write template notes is also required by the computer. This data includes vertical alinement, roadway and ditch dimensions, superelevation data, and cut and fill slope standards.

To simplify communications between the engineer and computer, forms are used to transmit necessary design data. There are four basic forms that must be submitted along with cross-section notes for the machine computation of template notes. These forms, together with a sample problem, are used in Figs. 10 through 14 to show the simplicity of the recorded data. The type of data recorded on the forms is summarized as follows:

1. Vertical curve data

    A. Station of each vertical P.I.
    B. Elevation of each vertical P.I.
    C. Length of each vertical curve
    D. Length of first and last vertical curve is recorded as zero

2. Horizontal curve data

    A. Beginning station of curve transition
    B. Beginning station of full superelevation
    C. Ending station of full superelevation
    D. Ending station of curve transition
    E. Rate of full superelevation
    F. Check mark for broken-back outside shoulder

3. Roadway dimensions

    A. Beginning station for respective dimensions
    B. Pavement or subgrade slopes of four planes
    C. Width of the four planes
    D. Surfacing depth
    E. Pivot point location of superelevation
    F. Check mark for special slope transitions

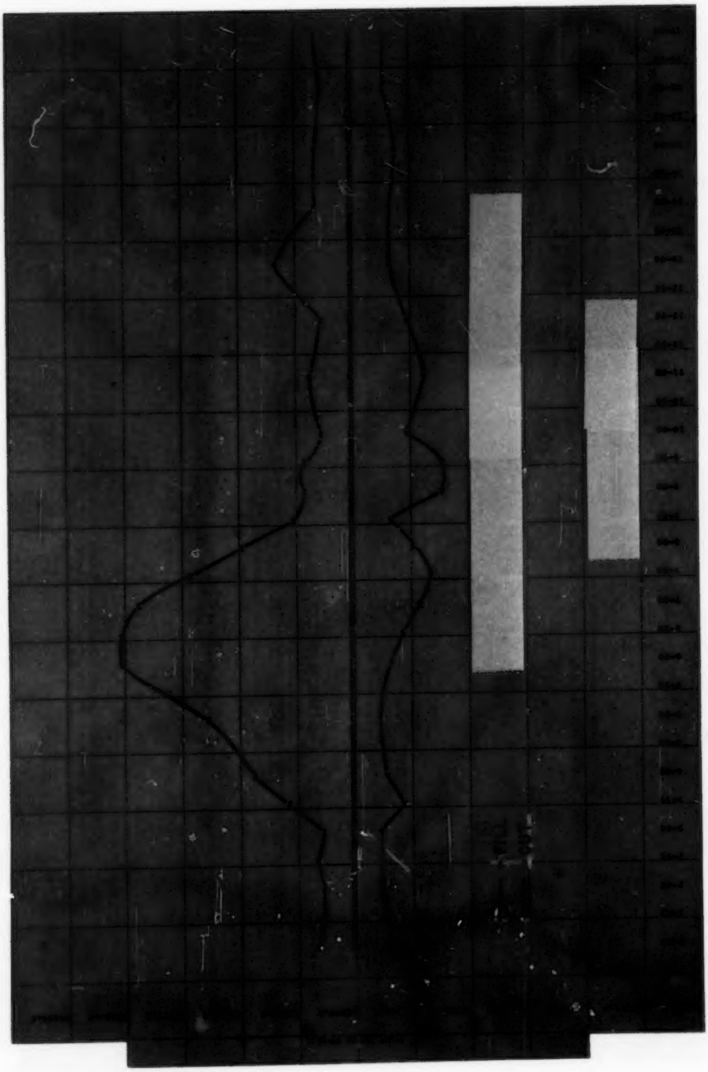


FIG. 7.—PLAN VIEW OF COMPUTED CATCH POINTS

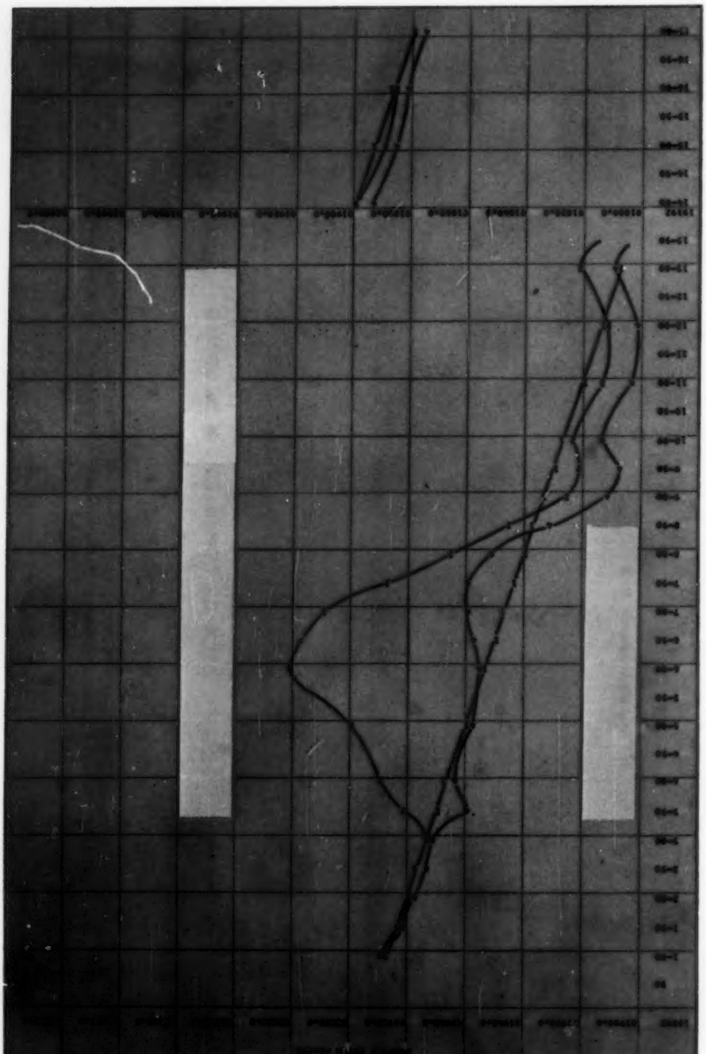


FIG. 8.–PROFILE VIEW OF COMPUTED CATCH POINTS

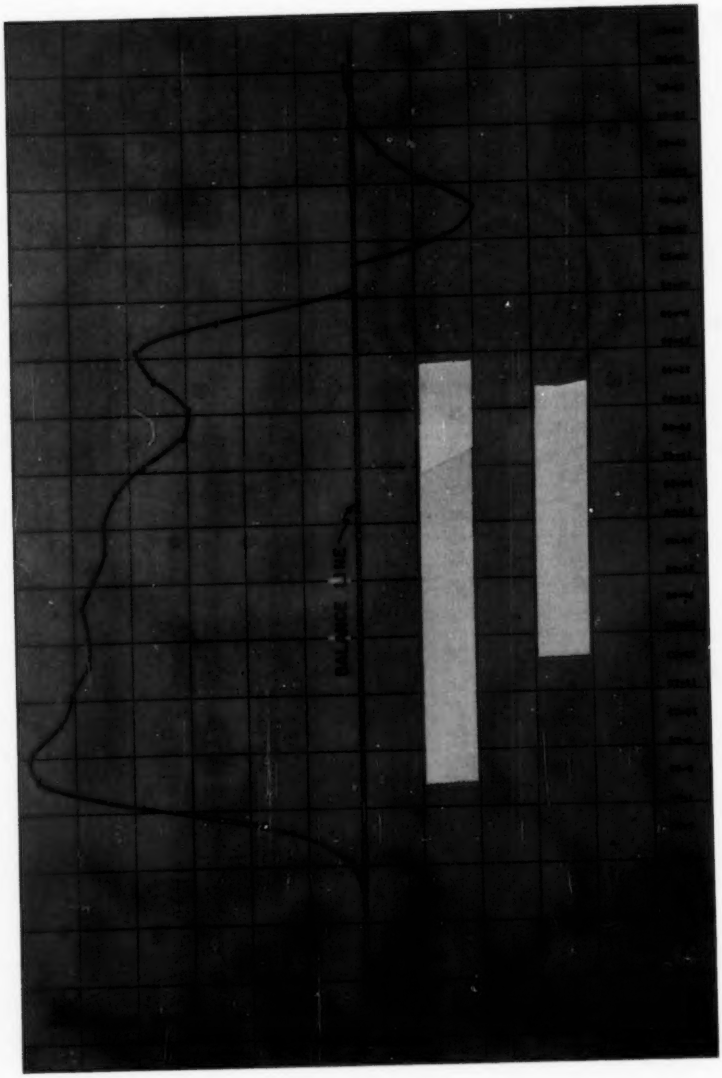


FIG. 9.—MACHINE PLOT OF MASS DIAGRAM

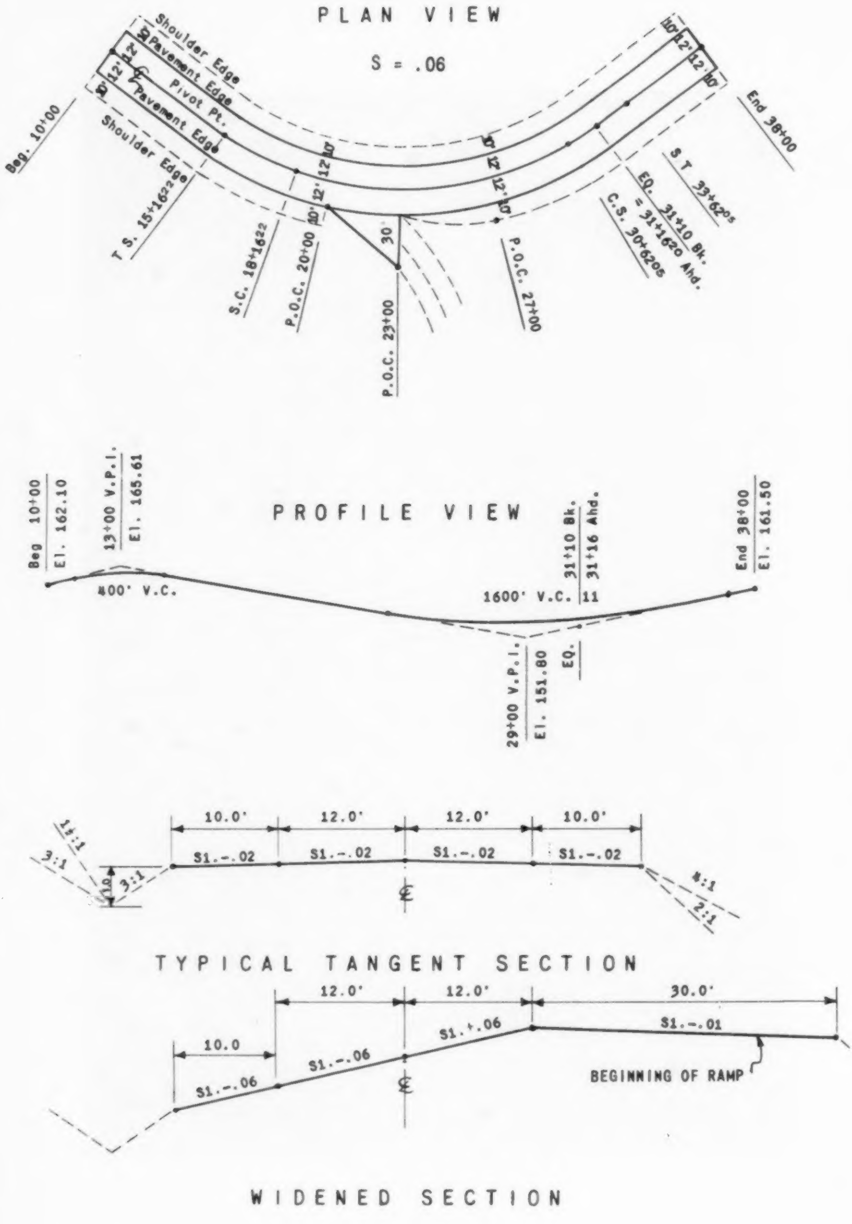
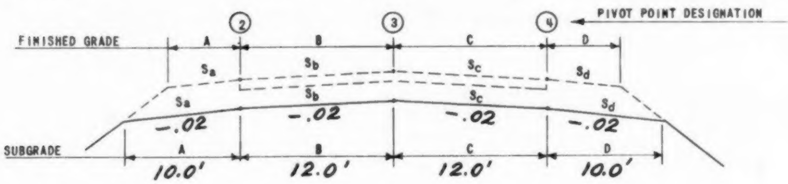


FIG. 10.—SAMPLE PROBLEM

1 PROJECT 6	7 11
	0

PROJECT NO. L-9876 LINE NO. "L"



8–15	16–18	19–21	22–24	25–27	28–31	32–35	36–39	40–43	44–46	47	48	49	50	51	52–53
STATION	RATE OF SLOPE				DISTANCES				SURF. DEPTH	PIVOT PT	MANUAL SLOPE TRANSITIONS				SECT. NO.
	S_a	S_b	S_c	S_d	A ②	B ③	C ④	D			S_a	S_b	S_c	S_d	
1.0——0	.020	.020	.020	.020	1.0——0	12.00	12.00	1.0——0	1.00	3	0——			——0	1
2.0——0				.020				1.0——0							2
2.0——0				.060 +				0——0							3
23+0——0				.010				3.0——0			0——	——0	1	0	4
23+0——0				0——0				0——0			0——			——0	5
27+0——0				.020				1.0——0							6
+															7
+															8
+															9
+															0
+															1
+															2
+															3
+															4
+															5
+															6
+															7
+															8
+															9
+															0

KEYPUNCH INSTRUCTIONS:
11-punch over Col. 15 where minus is shown. No overpunch if box is blank.
11-punch over Cols. 18, 21, 24 and 27 except no overpunch where plus sign is shown.
Zeros in all blank columns 1 to 53.

FIG. 11.—ROADWAY SECTION DATA

PROJECT NO. (1–6)
12

P S.H. No. 9 Project No. L-9876 Section Deep Cr. to Red Cr.

Line No. "L"

CARD NO. (7–8)	(10)	L C (12)	STATION OF VERTICAL P. I. (13–20)	VERTICAL CURVE LENGTH (21–24)	VERTICAL P. I. ELEVATION (25–30)
01	8		10+0—0	0—0	162.10
02	8		13+0—0	400	165.61
03	8		29+0—0	1600	151.80
04	8		38+0—0	0—0	161.50

NOTE:

1. Number each vertical P.I. 01 thru 15 under "Card No." Column.

2. First and last vertical P.I.'s in a group and angle points must have vertical curve length of zero.

EQUATIONS

STATIONS BACK		STATIONS AHEAD
31+10—0	=	31+16.20

FIG. 12.—VERTICAL CURVE DATA

4. Slope selection and ditch dimensions

   A. Beginning station for respective dimensions
   B. Standard cut slopes for four cut depths
   C. Standard fill slopes for four fill depths
   D. Adjustment dimensions for automatic widening
   E. Ditch dimensions
   F. Cut-off distance for medians

5. Station equations

   A. Each back and ahead station is listed respectively

Many detailed instructions are needed to properly record data for special or unusual conditions. These instructions should be printed on the forms for easy reference. The instructions can cover some of the following conditions: (1) for coding of stations recorded in the vicinity of overlapping station equations, (2) automatic widening transition sections, (3) automatic slope transitions, and (4) reverse and compound curve transitions with little or no tangent separating curves.

No two earthwork jobs are the same excepting for re-runs to investigate the most economical location of roadway. Thus flexibility must be stressed to handle any condition that should arise in roadway changes. More important is the fact that the earthwork quantities computed for design should be as the basis for payment to the contractor. With flexibility as the major consideration and a standardized system that can be used for reconnaissance, location or design, and construction, two programs have been used to produce template notes in the computer for the basic two-lane highway. A third program is necessary for the design of medians for multi-lane freeways with independent alinement and grade.

Machine Process.—A diagram of the machine computed template note process is shown in Fig. 15. It can be seen that data from each of the basic forms is punched onto data-processing cards. Cross-section notes are assembled with the roadway design data merely to inform the computer that template notes need be computed for each station where there are cross-section notes. An exception to the process is the use of station increment data for the computation of pavement or subgrade elevations determined from the same roadway design data as used for earthwork.

Profile Grade and Superelevation.—The basic vertical and horizontal alinement together with roadway dimensions are used as input to the profile grade and superelevation program. The output consists of five roadbed x and y coordinates rounded to the nearest 0.1 ft and referenced to the profile grade. The output for roadway elevations, computed from the same input data and used for staking, is the actual elevation of each of the five points computed to the nearest 0.01 ft.

The program computes the profile grade, adjusts the roadbed sections for superelevation, compensates automatically for equations and indicates location of equations, abrupt sections, tapered sections and bridges. The five basic points of the roadbed can be noted on the roadway section form (Fig. 11). For superelevated sections an additional point is computed for the broken-back shoulder on the outside of horizontal curves. As shown on the roadway section form, superelevation may be pivoted about either point 2, 3, or 4 in Fig. 11.

Slope Selection.—The roadbed x and y coordinates are merged with the cross-section notes station by station and together with the slope-selection design data are used as input to the next program in the process. The output of the program consists of completed template notes with the slopes as the two outside points much the same as explained in the basic machine process.

The program is set up to make several minor decisions. The computer first investigates one side of the roadway at a time to determine whether a side is in cut or fill, then to determine either the appropriate fill slope that is hinged at the sub-grade shoulder or the cut slope hinged at bottom of the ditch.

1 6
12 PROJECT

P S.H. No. 9 Project No. L-9876 SECTION Deep Cr. to Red Cr.

Line No. "L"

7 8 10 13 20 23 30 33 40 43 50 51 52 53 57 58 60

CARD NO.	12 H / V	STATIONING: BEGINNING OF TRANSITION 12	STATIONING: BEGINNING OF FULL SUPER 12	STATIONING: END OF FULL SUPER 12	STATIONING: END OF TRANSITION 12	* L R	L C	FULL RATE OF SUPER.	BROKEN BACK SHOULDER SLOPE
VOID									
01	9	15+16.22	18+16.22	30+62.05	33+62.05	8		.060	.00
	9								
	9								
	9								
	9								
	9								
	9								
	9								
	9								
	9								
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	9								
	9								
	9								
	9								
	9								

* Code an 8 for Curve to Left, Code 9 for Curve to Right.

1. This form defines to the computer the length and location of superelevation transition, full rate of superelevation to be attained, direction of curve, and broken-back shoulder slope where required.
2. Number each line serially beginning with 01 up to max. of 15 in the column headed "Card No".

4. Transition as used on this form does not include the 100 ft. run-off distance. Run-off is automatically computed.
5. Spiral and circular curves are treated the same by listing appropriate stations in the columns under "Stationing".
6. For broken-back shoulder on outside of curves, record the rate of slope in the appropriate column. Record zeroes in the column when broken-back shoulders are not required.
7. For reverse curves with less than 200 ft. of tangent and compound curves with no tangent, the computer will provide a smooth straight-line transition from "End of Full Super" of 1st curve to "Beginning of Full Super" of 2nd curve disregarding the S.T. and T.S. stationing.

FIG. 13.—SUPERELEVATION DATA

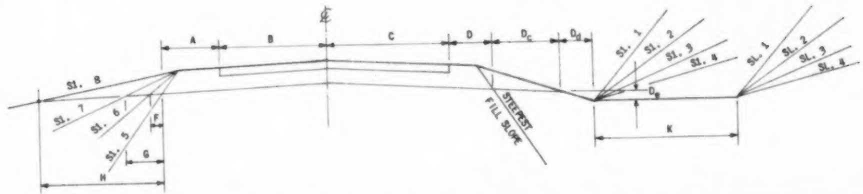
As can be noted on the slope-selection form, there are four cut slopes and four fill slopes at varying depths that are to be used in the determination of the proper slope. There are also maximum horizontal and vertical distances built into the program to insure that a slope on a side hill will not run parallel to existing ground.

The vertical limits are shown on the slope-selection form for each respective slope. Horizontal limits consist of the product of slope and vertical limits. For example if a 4:1 slope is recorded in the 5 ft to 10 ft vertical limit column, the horizontal limit would be the product of 4 x 10 or 40 ft.

70 PROJECT 75

P S.H. No. 9 Project No. L-9876 Section Deep Cr. to Red Cr.

Line No. "L"



58–69	1–3	4–6	7–9	10–12	13–15	16–18	19–21	22–24	25–27	28–30	31–33	34–36	37–39	40–42	43–45	46–48	49–51	52	53	54–56	57–59	60–63
FIRST STA. OF EACH DIFFERENT SECTION	CUT SLOPES				FILL SLOPES & DISTANCE CORRECTIONS							DITCH DIMENSIONS						DITCH CODE	11	FLAT BOTTOM DITCH		MEDIAN CUT OFF DISTANCE
												LEFT			RIGHT							
	OVER 15' Sl. 1	10'-15' Sl. 2	5'-10' Sl. 3	BELOW 5' Sl. 4	OVER 15' Sl. 5	10'-15' Sl. 6	F	5'-10' Sl. 7	G	BELOW 5' Sl. 8	H	D_c	D_e	D_d	D_c	D_e	D_d			LEFT K	RIGHT K	
10+0	1.5	1.5	3.0	3.0	2.0	2.0	0.0	4.0	0.0	4.0	0.0	0.0	1.0	3.0	0.0	1.0	3.0	0				0

* To retain median ditch thru fills, code in Column 52 as 8 for left ditch or 9 for right ditch.

NOTE:

1. For minus correction distance from steepest fill point for F, G, H, and D_c, place a minus sign in box above respective number.
2. For median cut off distance to left of center line of roadway place a minus sign in small box that is provided, leave small box blank for cut off distance to right.

KEYPUNCH INSTRUCTIONS:

1. Punch an 11-punch in each column where a minus sign is shown.
2. Punch a zero in column 52 when left blank

FIG. 14.—SLOPE-SELECTION DATA

The flattest slope is investigated first. If the vertical distance between the slope intercept and roadway shoulder is within the prescribed vertical limits, a horizontal distance check is made between the same two points. When the distance to the slope intercept exceeds the horizontal limit, the next slope is investigated, otherwise the flat slope is used. Here again where the cross-section notes were not of sufficient width, a slope connecting the outer point is determined.

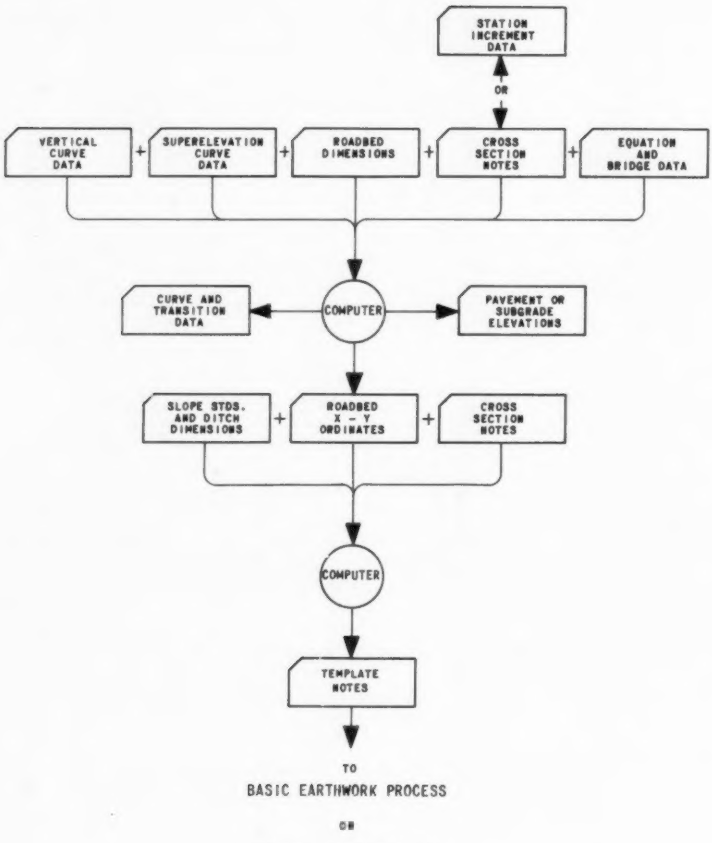


FIG. 15.—MACHINE COMPUTED TEMPLATE NOTES

Refinements in the slope-selection program were also necessary because of design standards. Since the fill slope is pivoted from the finished shoulder and the earthwork quantities are based on sub-grade data, the sub-grade shoulder point must be adjusted both vertically and horizontally. This has been a useful tool in cases where the shoulder must be widened for guard rail. The slope selection form can be coded for the automatic widening on the steeper slopes.

Where each roadway of a multi-lane freeway is on a common grade line and the median is to be graded, a space on the form is provided to record the distance out to median center line where a vertical slope is used. In this case the earthwork quantities of each roadway can be computed separately if requested by the engineer. However, the median design program to be discussed is generally used.

Template Check.—Another program is also used with the same roadway design input data to provide grade and horizontal curve transition data to insure the engineer that proper transitions were made and computations were made as instructed. Output data from this program consists of profile grade, percentage grade, and pavement and shoulder slopes through transitions. The percentage grade tangent to each 50-ft station through vertical curves is also shown as well as an interpolated station where the low or high point occurs on vertical curves. Pavement slopes are shown for each 25-ft station through horizontal curves as well as the station at beginning of crown run-off and the station where "crown super" is attained. A sample of this data is shown in Fig. 16 and was taken from the sample problem shown in Fig. 10, station 28+00 to station 32+64.13.

MEDIAN DESIGN

High-type rural freeways are more desirable where sections of the median can remain as undisturbed areas with natural vegetation. However, many sections, due to difference in profile grade or narrowing medians, require the complete grading of medians. Medians that are to be completely graded should then be designed on the computer.

To determine sections where the median-design program is to be used, earthwork quantities and slope-stake ordinates are generally computed for each roadway separately as if designing two two-lane highways. By utilizing the plan-view plot of the catch points as described previously, the sections where the complete median must be graded are visually determined. The plan-view plot need not be followed for narrow medians when it is known that the complete median will be graded.

Multi-lane freeway design by computers must be flexible for the multitude of medians that are used. Consideration must not only be given to the typical medians with standard ditches, but also the medians that connect roadways with both independent grades and alinement and with an independent grade for median ditches.

This type of computer program is being used for processing in a manner as outlined in Fig. 17. The template notes of each roadway are computed separately as discussed previously. The two sets of roadway template notes are then merged together station by station, and, with median dimensions and design features used as input to the median-design program. The program joins the two roadways together with the prescribed dimensions and references each roadway point to one common point such as the profile grade of one roadway. The output is a combined template of both roadways to be used either for earthwork or for recomputation to add frontage roads in the same manner.

Medians between roadways with independent grades and alinement have either constant slopes with variable ditches or constant ditch depths with variable slopes. There are also medians with one V-ditch, flat bottom ditches, ditches with independent grade, or two ditches separated with a raised mound.

IDENT.	STA.		V.C.L.	% GR.	TAN. ELEV	COR. ELEV	SLOPES A	B	C	D		4/07/60
L 9876 0	28+00.00			0.0107-	152.66	155.65	0.060-	0.060-	0.060	0.060	3	
	28+08.80	LEVEL		0.0000	152.59	155.65	0.060-	0.060-	0.060	0.060	3	
	28+50.00			0.0502	152.23	155.66	0.060-	0.060-	0.060	0.060	3	
	29+00.00	PIVC	1600	0.1111	151.80	155.70	0.060-	0.060-	0.060	0.060	3	
	29+50.00			0.1719	152.34	155.77	0.060-	0.060-	0.060	0.060	3	
	30+00.00			0.2328	152.89	155.87	0.060-	0.060-	0.060	0.060	3	
	30+50.00			0.2937	153.43	156.00	0.060-	0.060-	0.060	0.060	3	
	30+62.05	EFS		0.3082	153.56	156.04	0.060-	0.060-	0.060	0.060	3	
	30+75.00			0.3240	153.70	156.08	0.057-	0.057-	0.057	0.057	3	
	31+00.00			0.3546	153.97	156.16	0.052-	0.052-	0.052	0.052	3	
	31+10.00	BACK		0.3668	154.08	156.20	0.050-	0.050-	0.050	0.050	3	
	31+16.20	AHEAD		0.3668	154.08	156.20	0.050-	0.050-	0.050	0.050	3	
	31+25.00			0.3775	154.17	156.23	0.048-	0.048-	0.048	0.048	3	
	31+50.00			0.4078	154.45	156.33	0.043-	0.043-	0.043	0.043	3	
	31+75.00			0.4384	154.72	156.44	0.038-	0.038-	0.038	0.038	3	
	32+00.00			0.4687	154.99	156.55	0.033-	0.033-	0.033	0.033	3	
	32+25.00			0.4992	155.26	156.67	0.028-	0.028-	0.028	0.028	3	
	32+50.00			0.5296	155.53	156.80	0.023-	0.023-	0.023	0.023	3	
	32+64.13	CRSUP		0.5469	155.68	156.87	0.020-	0.020-	0.020	0.020	3	

FIG. 16.—TEMPLATE CHECK DATA

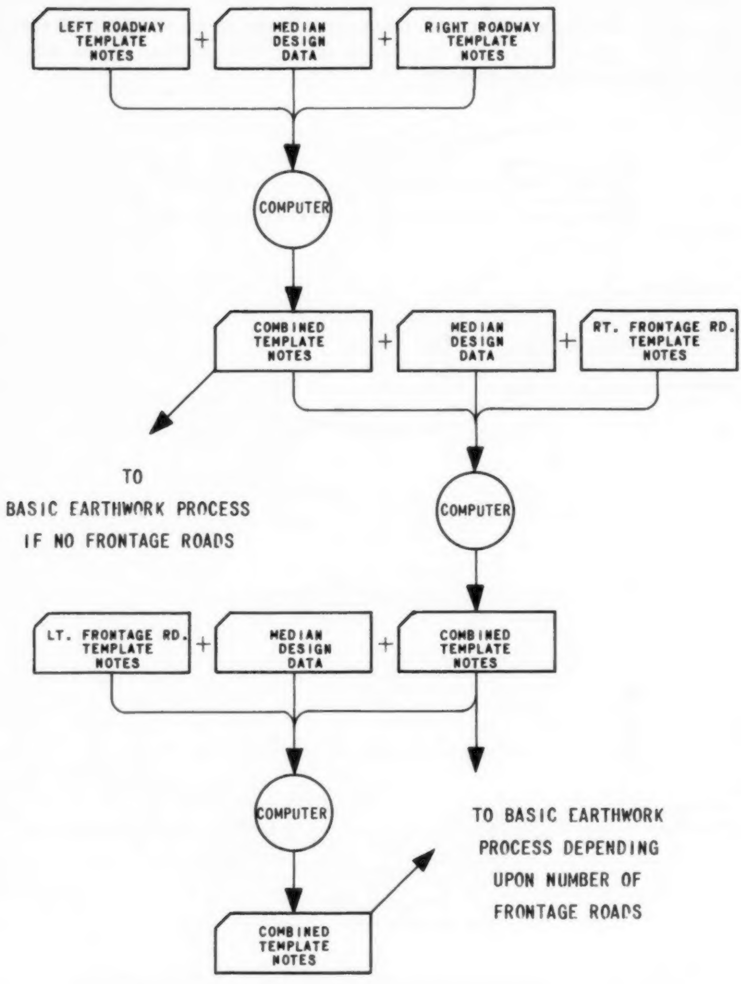


FIG. 17.—MACHINE COMPUTED TEMPLATE NOTES AND MEDIAN DESIGN

Because of the variety of median types a sketch of the median type with station-to-station limits is used in lieu of standard forms. Basic dimensions are required on the sketch which includes ditch dimensions D_e and D_d as well as offset distances from the pivot-point line of each roadway to the median center line. The offset distance for any of the median types when variable is submitted in the same manner as basic line-shift data. The median types are discussed and illustrated subsequently.

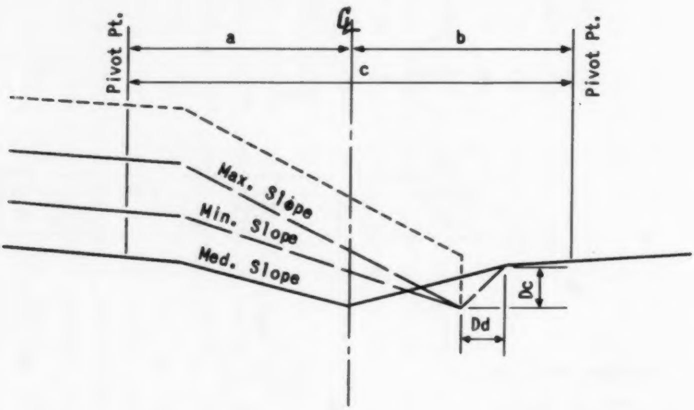


FIG. 18.—VARIABLE-OFFSET DITCH

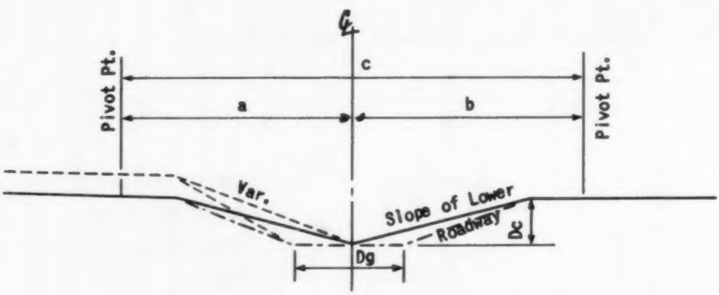


FIG. 19.—VARIABLE SLOPE AND CONSTANT DITCH DEPTH FROM LOWER ROADWAY

Variable Offset Ditch Median.—The variable-offset ditch type of median consists of a standard ditch depth below the lower roadway. The ditch will move laterally as the difference in profile grades of the two roadways varies. To control the location of the ditch and maintain pleasing slopes that do not exceed a given maximum and provide gentle transitions, three slopes connecting the high roadway and bottom of ditch are used by the computer to design the median. The slopes to be recorded are shown in Fig. 18.

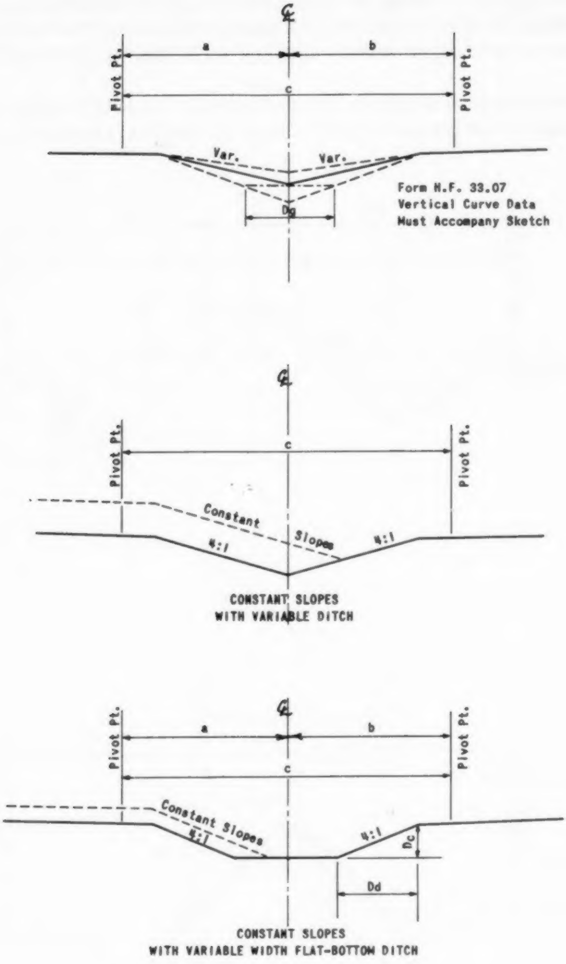
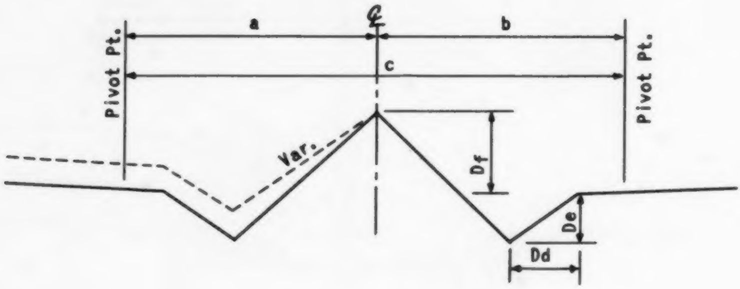


FIG. 20.—DEPRESSED MEDIANS

The maximum slope as shown is the steepest slope allowed for the particular class highway. Where the difference in elevations between the two roadways would require a steeper slope, the program would establish a vertical line at the ditch location to maintain a maximum slope. The vertical line could then be used as the height of the retaining wall that might be necessary in the design.

The minimum slope as shown is used merely to hold the ditch near the lower roadway until the differences in roadway elevations required a flatter slope.



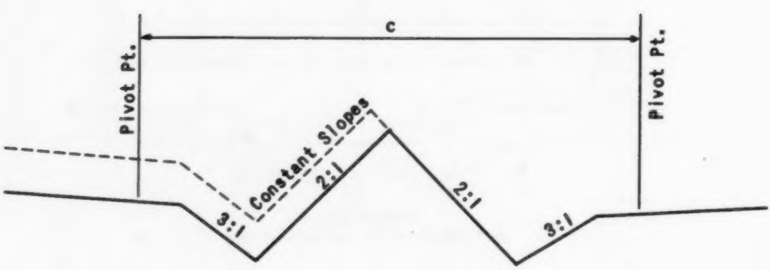


FIG. 21.—RAISED MEDIANS

As the two roadways approach the same elevation the ditch would automatically be shifted toward the center by interpolation. The dimensions and slopes shown are the only data required on the sketch submitted by the designer for computation.

Standard Depressed.—The standard depressed or V-ditch type median can be set up and designed by four methods depending on the variables that are used. The variables can consist of either or both of the slopes, ditch depths, or ditch width.

Where independent ditch grades are required for drainage, the vertical P.I. elevations must be recorded on the vertical-curve form. In this case, both the ditch slopes and ditch depths are variables and a function of independent ditch grade. Combinations of the depressed medians with dimensions required for the machine computation are shown in Figs. 19 and 20.

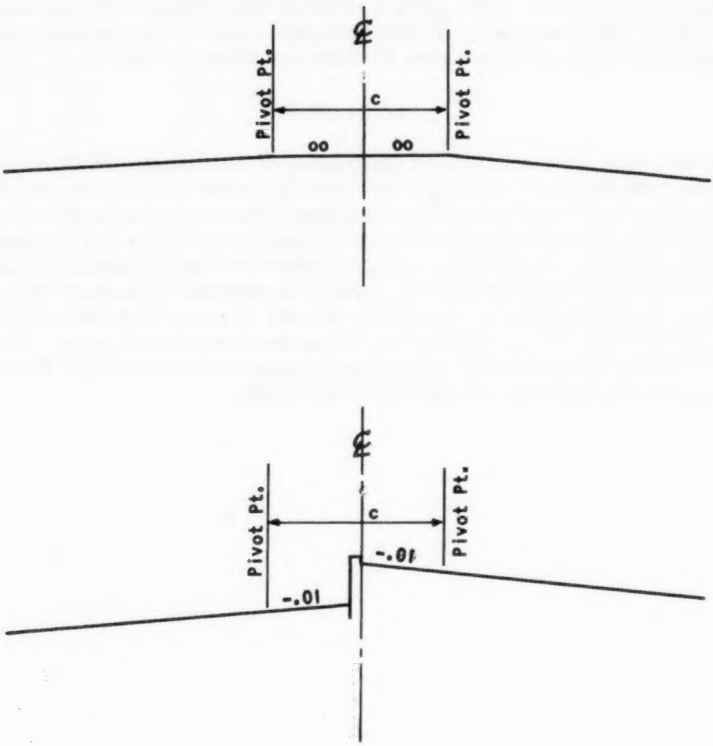


FIG. 22.—NARROW MEDIANS

Raised Medians.—The double ditch or raised median type used primarily to prevent headlight glare and to reduce head-on collisions can be designed on the computer by either of two methods. The difference again being the choice of variables. The raised mound may be set at a constant distance above the high roadway and located on the median center line, or, with the use of constant back slopes on the mound, the raised portion would vary both vertically and laterally as the difference in profile grade elevations of the two roadways vary. In either case, the computer program will determine the actual slope at each

station if variable slopes are used, or will locate the high point of the raised mound by intersection of the constant slopes.

Fig. 21 shows the various points of raised medians that are determined by the computer. Also shown are the dimensions required on the sketch from the design engineer.

Narrow Urban Area Medians.—Narrow medians will generally consist of a horizontal or sloping plane connecting the two roadways. Here the computer is used to connect the template notes of the two roadways with a single line. Where retaining walls must be incorporated into the median, it is possible to connect the horizontal planes from each roadway with a vertical line at the center line of the median. Here again a sketch of the median must accompany the other design data recorded on forms being submitted by the design engineer for computation. Narrow urban area medians are shown in Fig. 22.

CONCLUSIONS

Strides have been made in the processing of earthwork quantities and each new development only magnifies the need for more information on which to base design decisions for modern highways. The computer applications discussed herein were developed through the past three years and represent the first major change in approach to the subject in several decades. It is admitted that within a few short years the present earthwork techniques will appear crude as the techniques in this pioneering era of computers discussed herein are not the best. Many engineering firms have developed or are developing better earthwork processing techniques to improve the service to the engineer, reduce processing time, and decrease unit costs.

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DISCUSSION

ANALYZING AND PROJECTING TRAVEL DATA[a]

Discussion by Frank W. Herring

FRANK W. HERRING[8] F. ASCE.—The methodology used in the traffic-engineering analysis phases of the Mass Transportation Survey of the Washington Metropolitan Area has been clearly and succinctly described by the author. The reader cannot fail to be impressed by the thoroughness of the mathematical treatment and by the number of factors that have been taken into account in projecting future travel volumes. The Washington transportation study takes its place in the good company of the several studies in depth that have been made of urban travel behavior during the past few years, including those made of the Detroit, Chicago, St. Louis, Omaha, and Pittsburgh areas. Indeed, it has gone beyond most of those studies by introducing systematic travel assignments to common-carrier transportation as well as to automobile travel.

The Washington Metropolitan Area faces future transportation problems not unlike the problems faced by nearly all other large metropolitan cities. The traditional radial travel pattern, focused principally on the central business district and characterized by a heavy diurnal tidal flow of traffic back and forth between an outlying home and a central work place, cannot be the basis for estimating the need for travel facilities twenty years hence. In consequence of technological developments in communication, power transmission, and goods-handling, as well as in transportation itself, metropolitan growth is today (1960) featured by widespread dispersal and a huge appetite for hitherto open land. It is a wide dispersal not only of residences but also of work places, entertainment centers, retail centers, and nearly all other loci of travel generation or attraction. The result is a great dispersal of travel paths, analagous to the dispersal of trip-producing activities.

A forecast of the manner in which future population and future employment opportunities will be distributed goegraphically throughout the urbanized area is of central importance in estimating future travel demands. The forecast for metropolitan Washington D. C. is not different in kind from the forecasts that have been made for other metropolitan areas: relative stability of both population and jobs in the older, central core, and rapid growth of both in the outlying "suburban" areas are studied. For instance, a recently completed study of the future of the New York metropolitan region foresees a rise of 8,620,000 in population between 1955 and 1980 for the region as a whole, whereas for the five central-core counties of Manhattan, Brooklyn, Queens, Bronx, and Hudson, a population decline of 437,000 is anticipated. For employment, between 1956

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[a] June 1960, by Wilbur S. Smith (Proc. Paper 2513).

[8] Deputy Dir. for Comprehensive Planning, The Port of New York Authority, New York, N. Y.

and 1985, a rise of 3,053,000 for the total region is the estimate, of which 2,515,000 is looked for outside the central core.[9]

Future years will bring to American cities the task of accommodating a great rise in the volume of travel between outlying points, dispersed over ever wider areas. Channelization into a few routes of high travel density will not be possible, except at the expense of uneconomical circuity. Clearly, this will become a task for which old rules of thumb will not be adequate, and the development and application of a sound method of projecting future travel patterns and route volumes is a professional necessity for the engineer working in the field of urban transportation.

Closely related to this metropolitan growth character is the continuing trend toward increasing ownership of the automobile. The rise has two important aspects that need to be distinguished. First, there is the rise that is attributable solely to the rise in economic strength of urban people, to their increasing ability to afford and their increasing desires for ownership. Second, there is the rise that is attributable to the character of new residential development that accounts for nearly all of metropolitan population growth, low-density of land use, and a manner of using land that makes automobile ownership a virtual necessity. Low-density residential development entails high ownership of automobiles. As Nathan Cherniack, F. ASCE has pointed out,[10] data assembled for the Chicago Area Transportation Study demonstrate a remarkable correlation between households per net residential acre and automobile ownership (or, as Cherniack presents it, between households per acre and automobiles per acre) irrespective of personal income.

We must expect automobile ownership to rise even in those areas for which we anticipate no population growth. But we must also expect that metropolitan population growth increments will all be at high ownership rates. We must expect, therefore, that there will be increases in automobile travel mileage disproportionate to the increases in population and in employment.

Because the problem of projecting the volume and pattern of urban travel requires an assumption of a future urban form, a geographic distribution of travel generating and attracting points, quite different from the forms and distributions of the past, the "synthetic" or "interactance" technique used by the author and his colleagues has a basic superiority over the "growth factor" techniques that have been used so often. The technique is more complex, of course. But a large part of the problem is to estimate future travel volumes between areas now largely or even completely undeveloped, and between which present travel volumes are negligible or non-existent. Complex or not, the traffic projection method must provide for estimating the amount of travel produced or attracted by presently vacant areas and the strengths of the linkage between them.

Inescapably, traffic analysis and projection for a metropolitan area involves the manipulation of a vast array of data. The electronic computer has greatly facilitated this manipulation. But there is a grave danger here. The very fact that a glamorous gadget has been used may draw our attention too much to the gadgetry, and distract us from a thoughtful concern for the basic relationships involved. The computer will give the right answers only if it has been commanded to do the right things. There is still much debate among the specialists

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[9] "Metropolis, 1985," by Raymond Vernon, Harvard Univ. Press, 1960, Appendix tables.

[10] Nathan Cherniack, Highway Research Bd., Bulletin No. 253, p. 177 et seq.

over the proper parameters of travel behavior and over the ways in which they interact. John T. Lynch, M. ASCE, has said,[11] "It is fairly clear that there is no agreement among experts as to the best method for projecting future urban travel." There is not yet a professional consensus on what commands to give the computer. It is good to know that a goodly amount of imagination and ingenuity is being put into the question and that understanding of urban travel phenomena is being steadily advanced.

The author, wisely, warns us about this danger. He writes, about his "interactance" curves, "When applied directly, the curves produced 'relative' numbers of trips that represent average conditions. Trip estimates produced from the average curves were in correct proportions but may not have developed appropriate volumes." Again, he states, "Estimates of travel between districts are subject to considerably more variability than estimates of total trip production because so much depends on the quality and capacity of highways and transit facilities which link districts together." In other words, estimates of average travel behavior for the entire urban area are more reliable than estimates of travel between individual sub-areas. But the engineer's task of planning and designing travel facilities calls for just these specific inter-district travel volumes. It must be recognized that the analytical methods now available to us will yield only approximations of the travel volumes to be accommodated, with a margin of error that is difficult if not impossible to measure.

Moreover, as the author emphasizes, travel behavior is responsive to the ease and speed of travel the transportation system affords. If travel is easy and swift, trips are frequent and long. Conversely, if there are impediments to travel, trips are relatively short and infrequent. In other words, travel behavior in the future will reflect the quality of the travel facilities of the future.

At the outset, in a projection of future travel it becomes necessary to make some assumptions as to what that quality will be. Typically, the assumption is made, understandably, that the quality will be higher than that which prevails today, at least that travel will be faster and more convenient. This assumption conditions the entire problem of projection. The number of daily travel miles that will have to be provided for in the future will be greater if travel is improved, irrespective of growth in population, employment or automobile ownership. It may easily be that the electronic computer's estimate of future travel capacity requirements is as much a consequence of the assumed increased speed of travel as it is a consequence of metropolitan growth. Unfortunately, no urban transportation study yet made, so far as the writer is aware, has separated out the added plant requirements occasioned by the assumed increased ease of travel from those attributable to urban growth.

The possibility of speedier travel is without question a positive value to the community as a whole, as well as to the traveler. It manifests itself in wider choices of residential location for the workman and larger areas within which he can find employment of his skills, larger areas from which employers can draw their work forces, larger market areas for merchants, and larger areas from which producers can obtain their supplies. But it is a value that is costly to provide for. Somewhere there is a point of diminishing returns at which further increases in travel ease would cost more than the values derived from them. The provision of enough transportation plant to permit peak-hour travel to enjoy unimpeded flow at high speeds, thereby inducing even greater separ-

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[11] Highway Research Board, Bulletin No. 253, pp. 128-138.

ations between homes and work places than those now featuring our metropolitan areas, might turn out to be an extravagance.

Finally, the author's paper makes plain that the metropolitan growth pattern is one that will demand greater and greater use of automobile transportation in the future, and that the growth prospects for common-carrier transportation are limited. This outlook grows out of the way in which urban land is being utilized and is likely to be utilized in the future, at low density, spread over wide areas, with little over-all spatial organization. It does not grow out of the traveler's perversity or irrational behavior. Consequently, if such a prospect is adjudged uneconomical or undesirable and the intervention of public policy to modify it is considered, such intervention must be directed toward influencing the growth pattern itself rather than toward introducing a system of inducements or discouragements to the various forms of travel. Perhaps the development of the transportation system itself can be a potent influence in shaping the urban area of the future. But here again we have much to learn before we can use such a planning tool with skill and confidence.

HIGH TEMPERATURE EFFECTS ON BITUMINOUS MIXES[a]

Discussions by E. J. Woodward, Jr., Robert P. Lottman, F. N. Hveem, and John L. McRae

E. J. WOODWARD, JR.,[15] M. ASCE.—The effect of high mixing temperatures on bituminous mixes has been of great concern to the contractor-producer of asphalt paving materials. The demand for asphaltic paving to be delivered for lay down at high temperatures has caused much discussion. The need for materials at the highest practicable temperature is quite evident to the contractor who wishes to do a good and lasting job.

The Asphalt Institute and others have held to the theory that low mixing temperatures produce a better end product with longer life. Because many customers continually request paving materials at temperatures above that recommended by the Institute, a research program was instituted to determine whether a higher mixing temperature would effect the quality of the product.

The Marshall method of compaction was used because of availability of such equipment in the writer's laboratory facilities and because it is felt that the Marshall method is the best type of equipment for testing only asphalt paving materials reaction.

On completion of compaction, the specimens were allowed to cool to room temperature. The specimens were then labeled and their dimensions measured. Specific gravity determinations were made by weighing the test specimens in air and in water. The specimens were then stored on a smooth, level surface until ready for further testing.

Asphaltic concrete mixtures are commonly tested at a temperature of 140°F by the Marshall method. This test temperature was obtained by heating a water bath to 140°F. The Marshall test specimens were heated for 20 min in the 140°F water bath as indicated in the tables.

The composited results of this work are given in the tables. It can be noted that these results substantiate the data presented by the author.

[a] September 1960, by William H. Gotolski (Proc. Paper 2592).
[15] Vice Pres., Industrial Asphalt of Calif., Inc., Los Angeles, Calif.

TABLE 10.—MECHANICAL ANALYSIS (BY EXTRACTION)[a]

Passing sieve	Percent passing	
1/2	100.0	100
3/8	99.8	95-100
No. 4	81.8	65-85
No. 8	62.1	47-85
No. 16	47.8	
No. 30	34.2	21-32
No. 50	18.7	
No. 100	8.1	
No. 200	4.2	2-9

[a] Industrial "E" Mix Plant aggregate temperature 320°F
Penetration asphalt in storage tank - 39 Pen. @ 77°F
Temperature of paving asphalt 310°F

Penetrations for the extracted asphalt, all with 100 gm was as follows: for 5 sec 77°F --- 35; 3 sec 77°F --- 30; and 3 sec 104°F --- 94.

TABLE 11.—MARSHAL TESTS ON MIXTURE[a]

	1.	2.	3.
Height of Cylinder	2 7/16	2 7/16	2 7/16
Specific Gravity	2.248	2.259	2.255
Test Reading	495	520	500
Flow	10%	10%	10%
AVERAGE, Three Cylinders,			
Height	2 7/16		
Specific Gravity	2.254 (optimum bulk density)		
Test Reading	505 or 2125 pounds maximum load stability		
Flow	10%		
Densities and Voids:			
Specific Gravity, Mineral Aggregate passing 8 mesh, (Sand & Filler) 53.6% by volume	2.678		
Specific Gravity, Mineral Aggregate retained 8 mesh, (Rock) 33.1% by volume	2.658		
Specific Gravity, Asphalt Cement, 13.3% by volume	1.030(assumed)		
Apparent Density of above paving mixture	2.452		
Voids by volume, of average Marshall Test Cylinder	8.1%		

[a] 3 Cylinders, 20 min, 140°F

TABLE 12.—MECHANICAL ANALYSIS (BY EXTRACTION)[a]

Passing Sieve	Percent Passing	
1/2	100.0	100
3/8	99.2	95-100
No. 4	78.6	65-85
No. 8	53.3	47-65
No. 16	38.6	
No. 30	26.0	21-32
No. 50	15.2	
No. 100	7.6	
No. 200	4.4	2-9

[a] Industrial "E" Mix Plant aggregate temperature 375°F
Penetration asphalt in storage tank - 39 Pen. @ 77°F
Temperature of paving asphalt 310°F

Penetrations for the extracted asphalt, all with 100 gm are as follows: 5 sec 77°F --- 31; and 3 sec 77°F --- 26.

TABLE 13.—MARSHALL TEXTS ON MIXTURE[a]

	1.	2.	3.
Height of Cylinder	2 7/16	2 7/16	2 7/16
Specific Gravity	2.248	2.259	2.252
Test Reading	500	545	520
Flow	10%	10%	10%

AVERAGE, Three Cylinders,

Height	2 7/16
Specific Gravity	2.253
Test Reading	520 or 2190 pounds maximum load stability
Flow	10%

Densities and Voids:

Specific Gravity, Mineral Aggregate passing 8 mesh, (Sand & Filler) 44.7% by volume	2.671
Specific Gravity, Mineral Aggregate retained 8 mesh, (Rock) 40.4% by volume	2.661
Specific Gravity, Asphalt Cement 12.9% by volume	1.030(assumed)
Apparent Density of above paving mixture	2.456
Voids by volume, of average Marshall Test Cylinder	8.2%

[a] 3 Cylinders, 20 min, 140°F

Test results parallel to Gotolski's tests show that a mixing temperature of at least 350°F is very desirable in the production of commercial type asphalt pavings, for the following reasons:

1. This temperature assures dry aggregate for mixing.
2. The higher temperature gives better adhesiveness of asphalt to aggregate.
3. Loss of penetration is not apparent.
4. Easier workability in the field is noted.
5. Stability is obtained sooner.
6. Greater stability is obtained.
7. Raveling is reduced as the material is not worked cold.
8. Rolling compaction is more easily obtained.

For these reasons it is firmly believed that a mixing temperature of 350°F will give a better commercial asphalt paving mixture.

ROBERT P. LOTTMAN,[16] A. M. ASCE.—The effects of aggregate temperature on the change of asphalt properties (such as viscosity) during the mixing, hauling, paving, and compacting operations is of value to the improvement of mix design methods. Also, aggregate temperature has an effect on the economics of asphalt plant and paving operations.

When considering the advantages and disadvantages of mixing asphalt with aggregates heated to 375°F, several economic and quality implications appear to be of interest.

Advantages of Heating Aggregates to 375 F.—The average temperature of 375°F for aggregates during asphalt mixing may decrease asphalt viscosity during mixing and compaction to produce a greater mix density, and Hveem and Marshall stabilities. The additional effects of a harder asphalt, or an asphalt of lower viscosity when the mix reaches ambient temperatures may also contribute to greater stability values.

The higher aggregate temperature may result in a lower asphalt viscosity during mixing. It can contribute to shorter mixing times in the pugmill and greater plant production may result. It may also result in a "drier" coarse aggregate at time of asphalt mixing that can reduce moisture problems in the mix.

Disadvantages of Heating Aggregates to 375 F.—A relatively cool coarse aggregate temperature and a relatively hot fine aggregate temperature will be proportioned to give an average temperature of 375°F in the pugmill at a conventional plant. The relatively hot temperature of the fine aggregate (over 375°F) may overheat the asphalt to a greater extent than would be compensated with less overheating from the coarse aggregate (less than 375°F).

Excessive overheating of asphalt with aggregates at an average temperature of 375°F may actually be present if the penetration test is not exclusive or entirely reliable for predicting asphalt brittleness or cracking. Field work conducted in Ohio on recovered asphalt from 5-yr old pavements indicated that a low temperature (55°F), low speed ductility test (1 cm per min) was a better measure of asphalt cracking than the penetration test. The use of the penetration value seemed to work for most cases, but not for all. Apparently the penetration test does not predict entirely the cracking ability of all asphalts. Also the modified ductility test in itself may not indicate the true cracking proper-

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[16] Engrg. Experiment Station, Ohio State Univ. Columbus, Ohio.

ties of an asphalt, however, in view of the foregoing it may be possible that Hubbard and Gollomb's conclusions need some modification.

The economics of the plant and field operations may not improve due to increased fuel costs of heating aggregates to reach an average temperature of 375°F in the pugmill. Also mix production may decrease due to the smaller amount of aggregates in the dryer. The mix will be delivered at a relatively high temperature to the job and the result may be longer periods of waiting before rolling can proceed with present compaction machines.

When considering mix quality, the net effects achieved by mixing asphalt with aggregates at 375°F should not be overlooked if a superior mix can be produced. However, because the environment associated with asphaltic mixtures encompasses the equipment manufacturer, contractor, and user agency, in addition to the technologist, the entire operational effects should be considered if immediate field application is desired.

As a result of the use of the results of past research to inject meaning into data observations, the paper has given imputus to discussion in a controversial but very interesting area of bituminous mixture design.

F. N. HVEEM,[17] M. ASCE.—Although the relations expressed by the author in the conclusions are apparently derived from a statistical analysis, it is quite difficult to reconcile the results with other rather extensive studies involving the two stability methods.

The author states that the effect of preheating the asphalt in 5 gal cans is to decrease the Marshall stability and increase the Hveem stability as the preheat temperature is increased. It is difficult to understand how the relatively minor changes in the asphalt properties shown in Table 3 could cause such changes in stability. Further, a great deal of evidence exists to show that one of the principle factors influencing the Marshall stability is the cohesive strength of the binder whereas this factor has little or no effect on the Hveem Stabilometer value obtained at 140°F. On this basis one would expect an increase in Marshall stability instead a decrease as found by the author.

Characteristic results are attained when the effects of the aggregate temperatures are compared in the two methods of measuring stability. Although the author does not present data on the recovered asphalt penetration, it is reasonable to assume that the decrease in original penetration of the asphalt in the mix will be substantial at aggregate temperatures above 325°F. Such results would increase the cohesion or "tensile strength" effect and could materially change the Marshall stability, as found by the author.

Anyone interested in the durability of asphalt pavements should be concerned with the author's statements regarding the use of high aggregate temperatures during mixing.

The writer must take exception to the statement,

> "It was stated earlier that the specifications limiting mix temperature could be raised. That is, raise the limit from 325°F to 375°F. By raising the temperature to which the aggregate can be heated, a better coating of the aggregate is obtained."

Numerous individuals have agreed that the optimum asphalt viscosity for satisfactory coating at the time of mixing is between 75 sec to 150 sec Saybolt Furol.

[17] Materials and Research Engr. Calif. Div. of Highways, Sacramento, Calif.

Although some authorities believe that the upper limit may be raised somewhat, there is no available evidence that the minimum limit need be lowered.

In the case of the asphalt used by the author, Table 3 indicates that at 325°F the viscosity will fall within the above mentioned range and is only 35 sec at 350 F. On the basis of these observations, the writer cannot agree that raising the mixing temperature to the maximum recommended by the author is necessary to provide an adequate coating.

Finally there is ample evidence that many paving asphalts may be seriously hardened when mixed with aggregates above 325 F and the drop in penetration may exceed 50% of the original when temperatures approaching 375 F are used. Many such asphalts will comply with even more rigorous specifications than those now recommended by the ASTM and AASHO. It should be remembered, that 325 F is the maximum temperature for laboratory tests that are designed to indicate changes during mixing. There is no insurance against radical change in asphalt hardening rates if this maximum temperature is exceeded during the mixing operation.

The use of the Brown, Sparks, and Larsen criteria for predicting service life hardening is still open to question as to the extent of its application. An attempt to apply the criteria to ten different asphalts on the Zaca-Wigmore experimental project in California has not been successful in all cases.[18]

At the present time there is no real evidence to indicate that it is necessary to heat aggregates to 375°F under ordinary conditions in order to attain proper coating. Further, a survey of the literature clearly indicates that drastic undesirable changes may occur in many otherwise acceptable asphalts when temperatures of the aggregate in excess of 325°F are used in mixing operations.

JOHN L. McRAE,[19] M. ASCE.—Although tests were made on the asphalt in its original state and after heating in 5 gal lots, no data are given on the physical properties of the asphalt after mixing with the hot aggregate. Tests on asphalt recovered from the aggregate blends after mixing would naturally show much more change in physical properties because of the more drastic effects of heat on the asphalt in thin films that occur during mixing. It is believed that such data would greatly enhance the value of the paper. It would be particularly interesting to compare these values with the theoretical value of 72 computed by the author as representing the probable value after pig mill mixing at 375 F.

The author states that, in order to eliminate variables introduced by different sources of aggregate and asphalt, the tests were confined to materials from a single source for each material. He thus recognizes the possibility of variance due to use of different materials, but he fails to so qualify his conclusions. Also, his conclusion that the 375 F mixing temperature is satisfactory is based on theoretical calculations of change in penetration that would predict a nine-year life for the pavement. Some pavement engineers believe that a satisfactory life expectancy for a bituminous pavement based on aging of the asphalt alone (that is, assuming no overloading or inadequate foundations) should be approximately 18 yr, or twice the age selected by the author. It is well established that some asphalts are more affected by heat during mixing than others. This would cause the starting value of the in-place penetration to vary, with a consequent variance in the life expectancy of the pavement.

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18 ASTM Special Technical Publication No. 277, Amer. Soc. for Testing Materials.

19 Engr., Chf., Bituminous and Chemical Sect., Flexible Pavement Branch, Soils Div., U. S. Army Engr. Waterways Experiment Sta., Vicksburg, Miss.

It appears that conclusion 1, that states that the Marshall stability of both gradations decreases as the asphalt preheat temperature increases, is not well supported by the data. It can be seen that mix F, Fig. 3, shows a tendency to reverse the trend of reduction in stability with increased asphalt preheat temperature as the mixing temperature is increased.

Conclusion 2, that states that the Marshall stability of both gradations increases as the aggregate temperature at the time of mixing and compaction increases, may be based on too limited data. Another investigator[20] has presented data to show that the Marshall stability may show an increase with increased mixing temperature for a certain range of temperature, then decrease with increase in mixing temperature for a range, and then again show an increase for further increase in mixing temperature. In other words, the curve of Marshall stability versus mixing temperature showed first a peak, then a valley, and then started to rise again.

Verdi found that different grades of asphalt showed different temperatures at which this first peak stability occurred. He attributed this to variation in viscosity characteristics and showed that the maximum stability occurred at different mixing temperatures but at equivalent mixing viscosities.

The author states that mix F would not give good service because the voids were too high. This is indicated to be the Pennsylvania State Highway Department Specification FJ-1 surface course, but he makes no comment as to the actual experience with this mix in Pennsylvania. It would be interesting to know what the experience has been. If the author considers the void content too great at 6.0% asphalt and 50 blow Marshall compaction, it would appear that consideration should be given to overcoming this by increased compaction at the same asphalt content or, more likely, an increase in asphalt content while maintaining the same amount of compaction effort. It is not believed that a well-graded sand asphalt such as this should be rejected entirely on the basis of a high void content at a given asphalt content and degree of compaction because these variables can and should be readily adjusted to change the amount of voids in the mixture.

20 "Viscosity in Hot Mix Construction," by Verdi Adam, prepared for presentation at the 18th Annual SASHO Convention, November, 1959.

TRAFFIC BEHAVIOR AND FREEWAY RAMP DESIGN[a]

Discussion by Karl Moskowitz and Ichiro Fukutome

KARL MOSKOWITZ,[6] M. ASCE, and ICHIRO FUKUTOME.[7]—A study of traffic behavior and ramp design was conducted in California in 1958. The results of the entrance ramp portion of the study were published in 1959.[8]

It is reassuring to learn that the Texas studies confirmed the findings of the California study, particularly the finding that the angle of convergence must be flat in order to provide smooth operation.

As a result of the California study, the writers proposed a standard entrance ramp terminal. This design is shown in Fig. 24(a). Fig. 24(b) shows the authors' suggested design, with the writers' design overlaid in dashed lines. It will be noted that the two designs are about the same length and have other similarities. Besides length, the principal similarity is the long radius curve (2° in the authors' plan, 3000 ft radius in the writers' plan) used to lead the entering driver into a suitable merging path. The principal difference is in the amount of curb nose projected beyond the point at which the profile of the ramp comes tangent to the profile of the main roadway (Station 0+00 in Fig. 24(b).)

Effect of Curb Nose.—As one phase of the California studies, observations of traffic were made on a design in which the curb nose was projected until within 2 ft of the edge of the main roadway, followed by 500 ft of parallel lane, and then a 30:1 squeeze-off, as shown in Fig. 25. This compares with 400 ft followed by a 25:1 squeeze-off in the authors' design. (It would not be possible to construct a ramp exactly as shown in Fig. 20 because this would provide no clearance between the barrier curb and the edge of the main line). After making observations of this design, the curb nose was then pulled back 130 ft longitudinally and 8 ft laterally from the edge of the main roadway, as shown in the inset of Fig. 25, and another series of observations were made. As shown in Fig. 26, the wheel paths of the vehicles were unaffected by pulling back the curb. That is to say, they drove in a long angular path with the curb in either position.

The Interstate Standards (as interpreted in California) call for full shoulder clearance between the main line and any curb, whether mountable or barrier. However, in California the decision to go to full shoulder clearance was based on experience and was made independently.

Although the authors opinion, that it is desirable to pull traffic around to a nearly parallel path before entering the freeway is concurred in, it was found,

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[a] September 1960, by Charles Pinnell and Charles J. Keese (Proc. Paper 2604).

[6] Asst. Traffic Engr., Calif. Div. of Highways, Sacramento, Calif.

[7] Asst. Traffic Engr., Calif. Div. of Highways, Sacramento, Calif.

[8] "Traffic Behavior and On-Ramp Design," by Ichiro Fukutome and Karl Moskowitz, Bulletin No. 235, Highway Research Board, 1959.

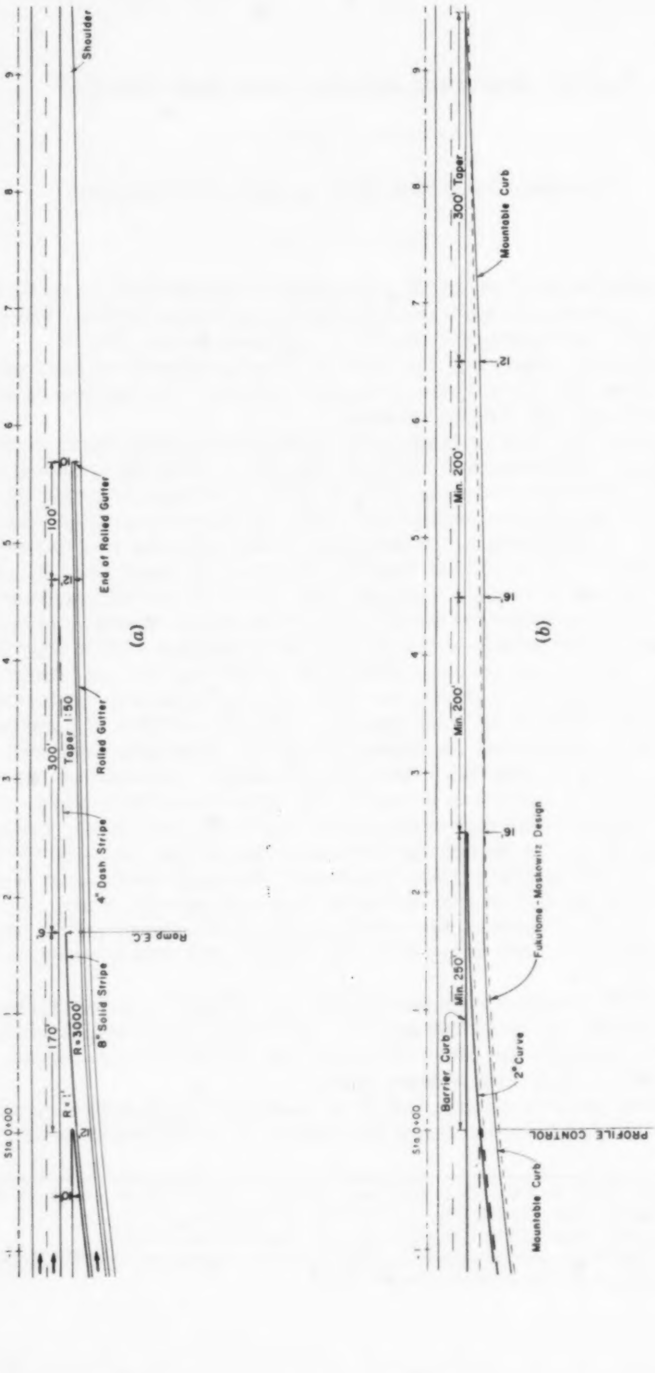
Shoulder
End of Rolled Gutter
100'
12'
Rolled Gutter
Taper 1:50
300'
4" Dash Stripe
9'
Ramp E.C.
8" Solid Stripe
170'
R=3000'
R=1'
Sta 0+00
(a)
300' Taper
Mountable Curb
Min. 200'
16'
Min. 200'
Fukutome - Moskowitz Design
Min. 250'
Barrier Curb
2° Curve
PROFILE CONTROL
Mountable Curb
(b)

FIG. 24

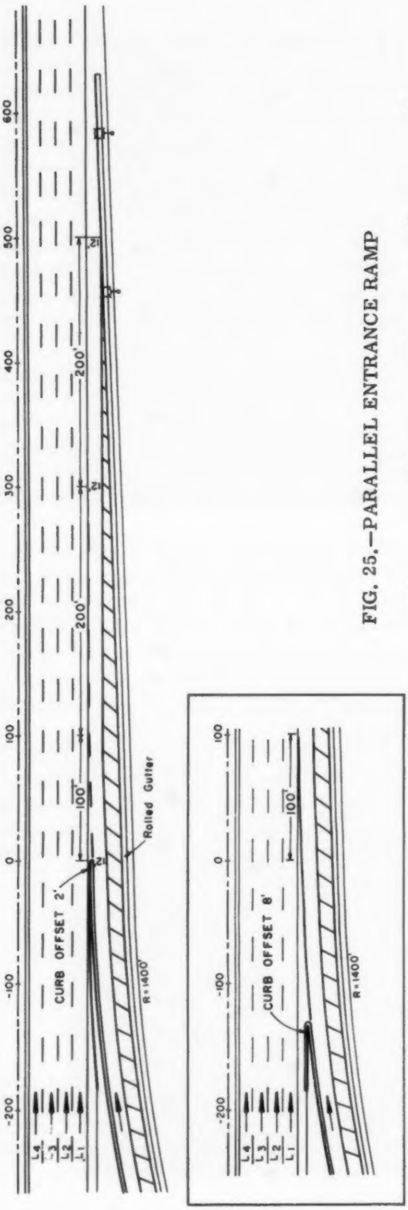

FIG. 25.—PARALLEL ENTRANCE RAMP

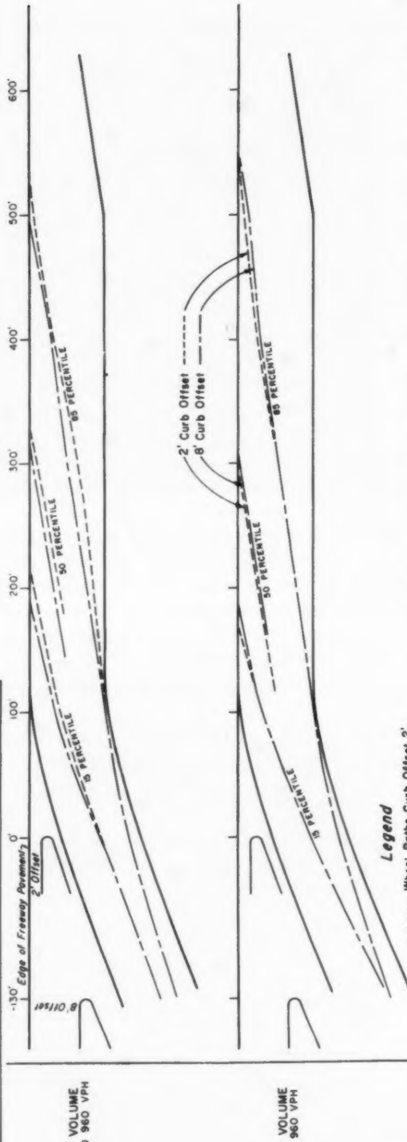

FIG. 26.—RIGHT REAR WHEEL PATHS FOR PARALLEL ON-RAMP

that this can be achieved without encroaching on the main line shoulder. It is inconceivable to contemplate a barrier curb with zero clearance from the main line.

Effect of Squeeze-off.—At Station 6+50 in the authors' design, a sharp angle squeeze-off (25:1) is introduced by means of a mountable curb that joins the main line of the freeway at Station 9+50. When a merging area joins a freeway that has a shoulder, as all Interstate freeways have, it is a mistake to carry an obstruction of any kind in front of the merging traffic. Any edge trimming of the on-ramp taper should end at the shoulder edge 10 ft from the edge of the through lane. Some designers, however, are still cutting off shoulders for bridges over 150 ft long, and if there is a bridge without shoulders just downstream from the merging area, the squeeze-off should never be as sharp as 25:1, or the very effect that Pinnell and Keese are trying to obviate will take place: Either the merging vehicles will shoot into the main line at too sharp an angle, or they will stop when they come to what looks like the "end" of the parallel ramp.

Findings in California indicate that very few drivers will drive the zig-zag path that a parallel acceleration lane is laid out to accommodate. In other words, most drivers will drive a long constant taper if there is room on the parallel acceleration lane for them to do so, and it is conceded that the authors' design will provide such room. It is felt, however, that it is desirable to encourage long flat approach angles by providing a guide on the right, that is constructed on this long flat angle (50:1).

Although it was found that with the parallel, or zig-zag, design, most vehicles will cut across the convex "corner" at the beginning of the ramp, and leave the triangle at the squeeze-off unused, as shown in Fig. 26, it was also noted that the occasional inexperienced driver, entering a parallel ramp with a sudden 25:1 squeeze-off at the end, is forced to make a decision as to whether he should go down and take a chance or cut in short. A constant taper design makes it easy for the driver to do what he is supposed to do, because he has a line to follow.

Photographs of merging maneuvers on long flat angles are shown in Fig. 27 through Fig. 30. In the foreground of Fig. 27 the ramp car is merging into a 166-ft, 2.7-sec gap in lane 1. Average headway between merged vehicles is 1.35 sec. Note that third car in lane 1 is moving to lane 2, anticipating that traffic in lane 1 will slow down slightly. The four cars now occupying 275 ft (4.3 sec) will stretch out to about 5.4 sec or 400 ft.

Instantaneous rate-of-flow in this picture is as follows:

Ramp		960 vph
Freeway	Lane 1 (near lane)	860 vph
	Lane 2	950 vph
	Lane 3	1400 vph
	Lane 4	220 vph
TOTAL		4390 vph

In the foreground of Fig. 28 the ramp car is merging into a 75-ft gap (1.2 sec) in lane 1. This shows that even with very light traffic, a gradual merge is necessary. After the merge, the average headway of the three cars in the foreground will be 0.6 sec, for a short length of time.

FIG. 27.—LIGHT TRAFFIC MERGING MANEUVERING

FIG. 28.—VERY LIGHT TRAFFIC MANEUVERING

FIG. 29.—HEAVY TRAFFIC MANEUVERING

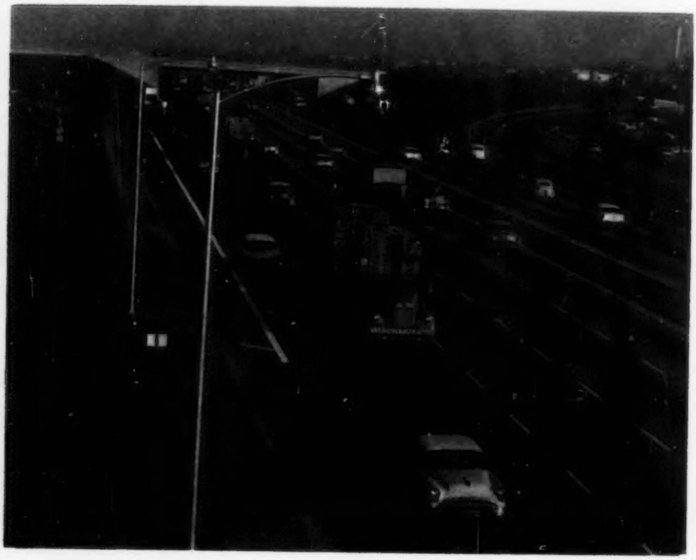

FIG. 30.—HEAVY COMMERCIAL TRAFFIC MANEUVERING

Instantaneous rate-of-flow in this picture is as follows:

Ramp		600 vph
Freeway	Lane 1 (near lane)	690 vph
	Lane 2	760 vph
	Lane 3	800 vph
	Lane 4	680 vph
TOTAL		3530 vph

In the foreground of Fig. 29 ramp car is merging into a 150-ft, 2.5-sec gap. Judging by the space between 2nd and 3rd cars in lane 1 (about 0.3 sec), 2nd car has yielded right-of-way to ramp vehicle. This is the only way that smooth flow can be obtained at saturated rate-of-flow.

Instantaneous rate-of-flow in this picture is as follows:

Ramp		1440 vph
Freeway	Lane 1	860 vph
	Lane 2	760 vph
	Lane 3	1600 vph
	Lane 4	2250 vph
TOTAL		6910 vph

Note in Fig. 30 that by gradual angle of convergence, ramp and freeway traffic will merge smoothly.

Instantaneous rate-of-flow in this picture is as follows:

Ramp		1200 vph
Freeway	Lane 1	700 vph
	Lane 2	600 vph
	Lane 3	1200 vph
	Lane 4	1800 vph
TOTAL		5500 vph

It will be noted that when ramp rate-of-flow is very high, many drivers in the ramp platoon enter the freeway simultaneously, when a comparatively long gap exists in the freeway traffic. This is considered to be desirable during these periods, but would not be possible if a curb were constructed between the ramp and the freeway.

Summary of Comments on Entrance Ramps.—The writers consider that the Texas study has confirmed the conclusions of the California study that entrances should be made on a long flat angle and that entrance ramp terminals should be standardized in shape. They do not concur with the details of the authors' proposed design, particularly the curbing, and offer in its place the design shown in Fig. 24. This design has been in place on the Eastshore Freeway

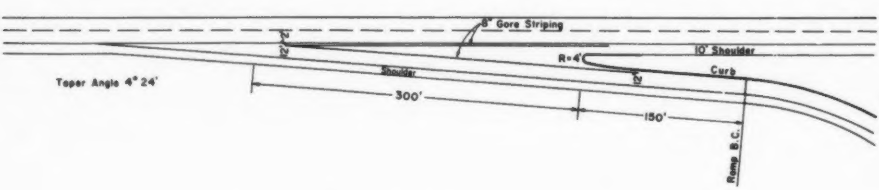

FIG. 31.—EXIT RAMP DELINEATION

(I.S. 80) in Berkeley, Calif. for over two years (as of 1961), and its operation is extremely satisfactory. During that time, 5,500,000 vehicles have used the ramp. One timid driver stopped in the approach roadway before entering the merging area and was hit by following cars. One accident happened when a disabled vehicle parked in the merging area. Other than this, there have been no accidents involving ramp vehicles or merging maneuvers. Weekday traffic volume on the freeway at this point is 100,000 (50,000 southbound), and is 8,000 on the ramp. Peak-hour ramp volume is 984 vehicles merging with one-way peak-hour volume on the freeway of 5,706, for a total of 6,690 vehicles per hour on the downstream leg. Merging speeds during this peak hour are between 35 mph and 55 mph. Hesitation or entrapment of entering vehicles is non-existent.

Exit Ramps.—The writers concur with Pinnell and Keese that exit ramps should provide a direct take-off with very distinct visual cues (that is to say, an angular deflection of about 4°), and that about 450 ft should be provided between the point of departure and the B.C. of the ramp curve, if there is a curve. However, the point of the gore must be traversable and indicated by paint or other pavement delineation. There must be a traversable neutral area in the gore; the distance should be about 300 ft from the point to the curb nose. A method of delineating the gore which has proven very satisfactory in California is shown in Fig. 3.

Because of the fact that paint or plastic lines do not show very well in rainy weather, it is believed that more research is needed to develop a traversable marking that will show in the dark when wet. It is unthinkable, however, to place a curb, even a "mountable" curb, at or near the point of the gore, much less along the edge of a main line freeway lane.

PROCEEDINGS PAPERS

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APRIL: 2428(ST4), 2429(HY4), 2430(PO2), 2431(SM2), 2432(PO2), 2433(ST4), 2434(EM2), 2435(PO2), 2436 (ST4), 2437(ST4), 2438(HY4), 2439(EM2), 2440(EM2), 2441(ST4), 2442(SM2), 2443(HY4), 2444(ST4), 2445 (EM2), 2446(ST4), 2447(EM2), 2448(SM2), 2449(HY4), 2450(ST4), 2451(HY4), 2452(HY4), 2453(EM2), 2454 (EM2), 2455(EM2)[c], 2456(HY4)[c], 2457(PO2)[c], 2458(ST4)[c], 2459(SM2)[c].

MAY: 2460(AT1), 2461(ST5), 2462(AT1), 2463(AT1), 2464(CP1), 2465(CP1), 2466(AT1), 2467(AT1), 2468(SA3), 2469(HY5), 2470(ST5), 2471(SA3), 2472(SA3), 2473(ST5), 2474(SA3), 2475(ST5), 2476(SA3), 2477(ST5), 2478 (HY5), 2479(SA3), 2480(ST5), 2481(SA3), 2482(CO2), 2483(CO2), 2484(HY5), 2485(HY5), 2486(AT1)[c], 2487 (CP1)[c], 2488(CO2)[c], 2489(HY5)[c], 2490(SA3)[c], 2491(ST5)[c], 2492(CP1), 2493(CO2).

JUNE: 2494(IR2), 2495(IR2), 2496(ST6), 2497(EM3), 2498(EM3), 2499(EM3), 2500(EM3), 2501(SM3), 2502 (EM3), 2503(PO3), 2504(WW2), 2505(EM3), 2506(HY6), 2507(WW2), 2508(PO3), 2509(ST6), 2510(EM3), 2511 (EM3), 2512(ST6), 2513(HW2), 2514(HY6), 2515(PO3), 2516(EM3), 2517(WW2), 2518(WW2), 2519(EM3), 2520 (PO3), 2521(HY6), 2522(SM3), 2523(ST6), 2524(HY6), 2525(HY6), 2526(HY6), 2527(IR2), 2528(ST6), 2529 (HW2), 2530(IR2), 2531(HY6), 2532(EM3)[c], 2533(HW2)[c], 2534(WW2), 2535(HY6)[c], 2536(IR2)[c], 2537(PO3)[c], 2538(SM3)[c], 2539(ST6)[c], 2540(WW2)[c].

JULY: 2541(ST7), 2542(ST7), 2543(SA4), 2544(ST7), 2545(ST7), 2546(HY7), 2547(ST7), 2548(SU2), 2549(SA4), 2550(SU2), 2551(HY7), 2552(ST7), 2553(SU2), 2554(SA4), 2555(ST7), 2556(SA4), 2557(SA4), 2558(SA4), 2559(ST7), 2560(SU2)[c], 2561(SA4)[c], 2562(HY7)[c], 2563(ST7)[c].

AUGUST: 2564(SM4), 2565(EM4), 2566(ST8), 2567(EM4), 2568(PO4), 2569(PO4), 2570(HY8), 2571(EM4), 2572(EM4), 2573(EM4), 2574(SM4), 2575(EM4), 2576(EM4), 2577(HY8), 2578(EM4), 2579(PO4), 2580 (EM4), 2581(ST8), 2582(ST8), 2583(EM4)[c], 2584(PO4)[c], 2585(ST8)[c], 2586(SM4)[c], 2587(HY8)[c].

SEPTEMBER: 2588(IR3), 2589(IR3), 2590(WW3), 2591(IR3), 2592(HW3), 2593(IR3), 2594(IR3), 2595(IR3), 2596 (HW3), 2597(WW3), 2598(IR3), 2599(WW3), 2600(WW3), 2601(WW3), 2602(WW3), 2603(WW3), 2604(HW3), 2605(SA5), 2606(WW3), 2607(SA5), 2608(ST9), 2609(SA5)[c], 2610(IR3), 2611(WW3)[c], 2612(ST9)[c], 2613(IR3)[c], 2614(HW3)[c].

OCTOBER: 2615(EM5), 2616(EM5), 2617(ST10), 2618(SM5), 2619(EM5), 2620(EM5), 2621(ST10), 2622(EM5), 2623(SM5), 2624(EM5), 2625(SM5), 2626(SM5), 2627(EM5), 2628(EM5), 2629(ST10), 2630(ST10), 2631(PO5)[c], 2632(EM5)[c], 2633(ST10), 2634(ST10), 2635(ST10)[c], 2636(SM5)[c].

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DECEMBER: 2668(ST12), 2669(IR4), 2670(SM6), 2671(IR4), 2672(IR4), 2673(IR4), 2674(ST12), 2675 (EM6), 2676(IR4), 2677(HW4), 2678(ST12), 2679(EM6), 2680(ST12), 2681(SM6), 2682(IR4), 2683(SM6), 2684(SM6), 2685(IR4), 2686(EM6), 2687(EM6), 2688(EM6), 2689(EM6), 2690(EM6), 2691(EM6)[c], 2692 (ST12), 2693(ST12), 2694(HW4)[c], 2695(IR4)[c], 2696(SM6)[c], 2697(ST12)[c].

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JANUARY: 2698(PP1), 2699(PP1), 2700(HY1), 2701(SA1), 2702(SU1), 2703(ST1), 2704(ST1), 2705(SU1), 2706 (HY1), 2707(HY1), 2708(HY1), 2709(PO1), 2710(HY1), 2711(HY1), 2712(ST1), 2713(HY1), 2714(PO1), 2715 (ST1), 2716(HY1), 2717(SA1), 2718(SA1), 2719(SU1)[c], 2720(SA1)[c], 2721(ST1), 2722(PP1)[c], 2733(PO1)[c], 2724 (HY1)[c], 2725(ST1)[c].

FEBRUARY: 2726(WW1), 2727(EM1), 2728(EM1), 2729(WW1), 2730(WW1), 2731(EM1), 2732(SM1), 2733(WW1), 2734(SM1), 2735(EM1), 2736(EM1), 2737(PL1), 2738(PL1), 2739(PL1), 2740(PL1), 2741(EM1), 2742(ST2), 2743(EM1), 2744(WW1), 2745(WW1), 2746(SM1), 2747(WW1), 2748(EM1), 2749(WW1), 2750(WW1)[c], 2751 (EM1)[c], 2752(SM1)[c], 2753(PL1)[c], 2754(ST2)[c], 2755(PL1).

MARCH: 2756(HY2), 2757(IR1), 2758(AT1), 2759(CO1), 2760(HY2), 2761(IR1), 2762(IR1), 2763(HY2), 2764 (ST3), 2765(HY2), 2766(HW1), 2767(SA2), 2768(CO1), 2769(IR1), 2770(HY2), 2771(SA2), 2772(HY2), 2773 (CO1), 2774(AT1), 2775(IR1), 2776(HY2), 2777(HY2), 2778(SA2), 2779(ST3), 2780(HY2), 2781(HY2)[c], 2782 (HW1)[c], 2783(SA2)[c], 2784(CO1), 2785(CO1)[c], 2786(IR1)[c], 2787(ST3)[c], 2788(AT1)[c], 2789(HW1).

c. Discussion of several papers, grouped by divisions.

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APRIL: 2428(ST4), 2429(HY4), 2430(PO2), 2431(SM2), 2432(PO2), 2433(ST4), 2434(EM2), 2435(PO2), 2436(ST4), 2437(ST4), 2438(HY4), 2439(EM2), 2440(EM2), 2441(ST4), 2442(SM2), 2443(HY4), 2444(ST4), 2445(EM2), 2446(ST4), 2447(EM2), 2448(SM2), 2449(HY4), 2450(ST4), 2451(HY4), 2452(HY4), 2453(EM2), 2454(EM2), 2455(EM2)[c], 2456(HY4)[c], 2457(PO2)[c], 2458(ST4)[c], 2459(SM2)[c].

MAY: 2460(AT1), 2461(ST5), 2462(AT1), 2463(AT1), 2464(CP1), 2465(CP1), 2466(AT1), 2467(AT1), 2468(SA3), 2469(HY5), 2470(ST5), 2471(SA3), 2472(SA3), 2473(ST5), 2474(SA3), 2475(ST5), 2476(SA3), 2477(ST5), 2478(HY5), 2479(SA3), 2480(ST5), 2481(SA3), 2482(CO2), 2483(CO2), 2484(HY5), 2485(HY5), 2486(AT1)[c], 2487(CP1)[c], 2488(CO2)[c], 2489(HY5)[c], 2490(SA3)[c], 2491(ST5)[c], 2492(CP1), 2493(CO2).

JUNE: 2494(IR2), 2495(IR2), 2496(ST6), 2497(EM3), 2498(EM3), 2499(EM3), 2500(EM3), 2501(SM3), 2502(EM3), 2503(PO3), 2504(WW2), 2505(EM3), 2506(HY6), 2507(WW2), 2508(PO3), 2509(ST6), 2510(EM3), 2511(EM3), 2512(ST6), 2513(HW2), 2514(HY6), 2515(PO3), 2516(EM3), 2517(WW2), 2518(WW2), 2519(EM3), 2520(PO3), 2521(HY6), 2522(SM3), 2523(ST6), 2524(HY6), 2525(HY6), 2526(HY6), 2527(IR2), 2528(ST6), 2529(HW2), 2530(IR2), 2531(HY6), 2532(EM3)[c], 2533(HW2)[c], 2534(WW2), 2535(HY6)[c], 2536(IR2)[c], 2537(PO3)[c], 2538(SM3)[c], 2539(ST6)[c], 2540(WW2)[c].

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AUGUST: 2564(SM4), 2565(EM4), 2566(ST8), 2567(EM4), 2568(PO4), 2569(PO4), 2570(HY8), 2571(EM4), 2572(EM4), 2573(EM4), 2574(SM4), 2575(EM4), 2576(EM4), 2577(HY8), 2578(EM4), 2579(PO4), 2580(EM4), 2581(ST8), 2582(ST8), 2583(EM4)[c], 2584(PO4)[c], 2585(ST8)[c], 2586(SM4)[c], 2587(HY8)[c].

SEPTEMBER: 2588(IR3), 2589(IR3), 2590(WW3), 2591(IR3), 2592(HW3), 2593(IR3), 2594(IR3), 2595(IR3), 2596(HW3), 2597(WW3), 2598(IR3), 2599(WW3), 2600(WW3), 2601(WW3), 2602(WW3), 2603(WW3), 2604(HW3), 2605(SA5), 2606(WW3), 2607(SA5), 2608(ST9), 2609(SA5)[c], 2610(IR3), 2611(WW3)[c], 2612(ST9)[c], 2613(IR3)[c], 2614(HW3)[c].

OCTOBER: 2615(EM5), 2616(EM5), 2617(ST10), 2618(SM5), 2619(EM5), 2620(EM5), 2621(ST10), 2622(EM5), 2623(SM5), 2624(EM5), 2625(SM5), 2626(SM5), 2627(EM5), 2628(EM5), 2629(ST10), 2630(ST10), 2631(PO5)[c], 2632(EM5)[c], 2633(ST10), 2634(ST10), 2635(ST10)[c], 2636(SM5)[c].

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DECEMBER: 2668(ST12), 2669(IR4), 2670(SM6), 2671(IR4), 2672(IR4), 2673(IR4), 2674(ST12). 2675(EM6), 2676(IR4), 2677(HW4), 2678(ST12), 2679(EM6), 2680(ST12), 2681(SM6), 2682(IR4), 2683(SM6), 2684(SM6), 2685(IR4), 2686(EM6), 2687(EM6), 2688(EM6), 2689(EM6), 2690(EM6), 2691(EM6)[c], 2692(ST12), 2693(ST12), 2694(HW4)[c], 2695(IR4)[c], 2696(SM6)[c], 2697(ST12)[c].

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FEBRUARY: 2726(WW1), 2727(EM1), 2728(EM1), 2729(WW1), 2730(WW1), 2731(EM1), 2732(SM1), 2733(WW1), 2734(SM1), 2735(EM1), 2736(EM1), 2737(PL1), 2738(PL1), 2739(PL1), 2740(PL1), 2741(EM1), 2742(ST2), 2743(EM1), 2744(WW1), 2745(WW1), 2746(SM1), 2747(WW1), 2748(EM1), 2749(WW1), 2750(WW1)[c], 2751(EM1)[c], 2752(SM1)[c], 2753(PL1)[c], 2754(ST2)[c], 2755(PL1).

MARCH: 2756(HY2), 2757(IR1), 2758(AT1), 2759(CO1), 2760(HY2), 2761(IR1), 2762(IR1), 2763(HY2), 2764(ST3), 2765(HY2), 2766(HW1), 2767(SA2), 2768(CO1), 2769(IR1), 2770(HY2), 2771(SA2), 2772(HY2), 2773(CO1), 2774(AT1), 2775(IR1), 2776(HY2), 2777(HY2), 2778(SA2), 2779(ST3), 2780(HY2), 2781(HY2)[c], 2782(HW1)[c], 2783(SA2)[c], 2784(CO1), 2785(CO1)[c], 2786(IR1)[c], 2787(ST3)[c], 2788(AT1)[c], 2789(HW1).

c. Discussion of several papers, grouped by divisions.